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Pai et al.

(10) **Patent No.: US 9,304,146 B2**
(45) **Date of Patent: Apr. 5, 2016**

(54) **RADIO-FREQUENCY REFLECTOMETRY SCANNING TUNNELING MICROSCOPE**

(71) Applicant: **National Taiwan University**, Taipei (TW)

(72) Inventors: **Woei-Wu Pai**, Taipei (TW); **Huan-Hsin Li**, New Taipei (TW); **I-Jan Chen**, Taipei (TW); **Yen-Cheng Chao**, Taoyuan (TW)

(73) Assignee: **NATIONAL TAIWAN UNIVERSITY**, Taipei (TW)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/490,812**

(22) Filed: **Sep. 19, 2014**

(65) **Prior Publication Data**

US 2015/0026847 A1 Jan. 22, 2015

Related U.S. Application Data

(63) Continuation-in-part of application No. 14/037,024, filed on Sep. 25, 2013, now Pat. No. 8,863,311.

(30) **Foreign Application Priority Data**

Jul. 18, 2013	(TW)	102125746 A
Jul. 17, 2014	(TW)	103124553 A

(51) **Int. Cl.**
G01Q 60/16 (2010.01)

(52) **U.S. Cl.**
CPC ***G01Q 60/16*** (2013.01)

(58) **Field of Classification Search**
CPC G01Q 60/16
USPC 850/21
See application file for complete search history.

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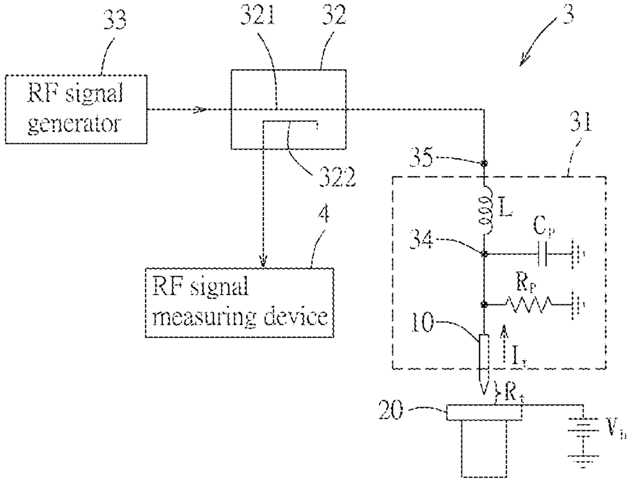
Primary Examiner — Phillip A Johnston
(74) *Attorney, Agent, or Firm* — Birch, Stewart, Kolasch & Birch, LLP

(57) **ABSTRACT**

An RF reflectometry scanning tunneling microscope is suitable for observing a surface of an object, and includes a probe that cooperates with the object to form a tunneling resistor therebetween, an RF resonant circuit that cooperates with the tunneling resistor to form a LCR resonant circuit including an inductor connected to a parallel connection of a capacitor, a resistor and the tunneling resistor, a directional coupler receiving an RF signal and outputting the RF signal to the LCR resonant circuit, and an RF signal measuring device that generates a scanning result associated with the surface of the object based on a reflected RF signal resulting from reflection of the RF signal by the LCR resonant circuit.

19 Claims, 23 Drawing Sheets



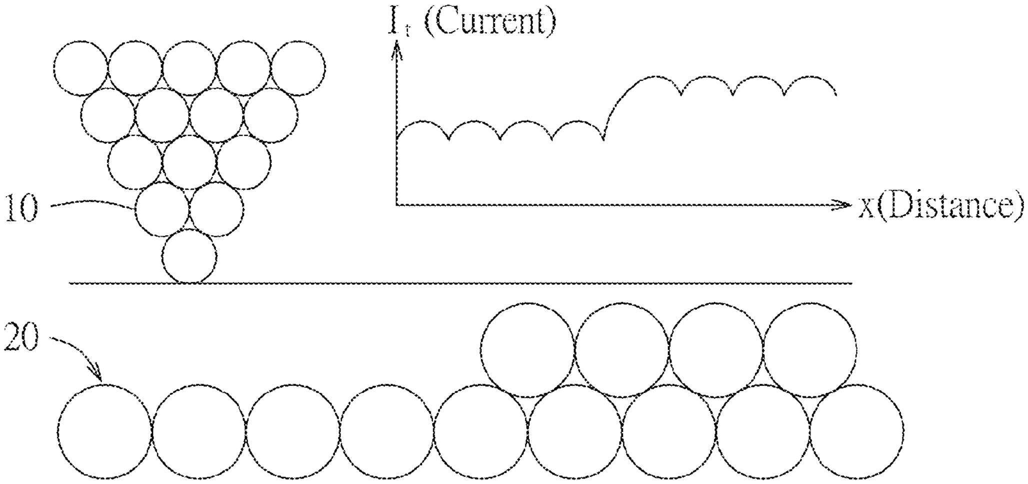


FIG.1
PRIOR ART

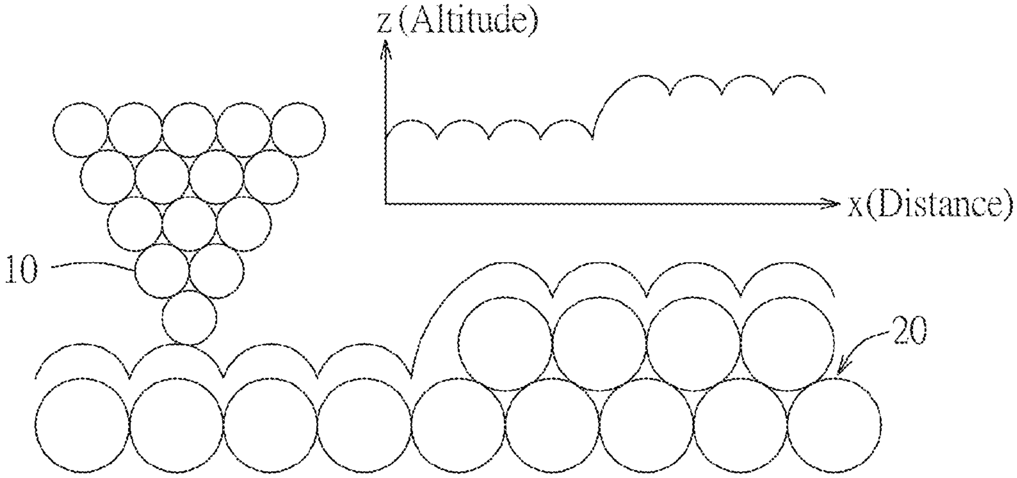


FIG.2
PRIOR ART

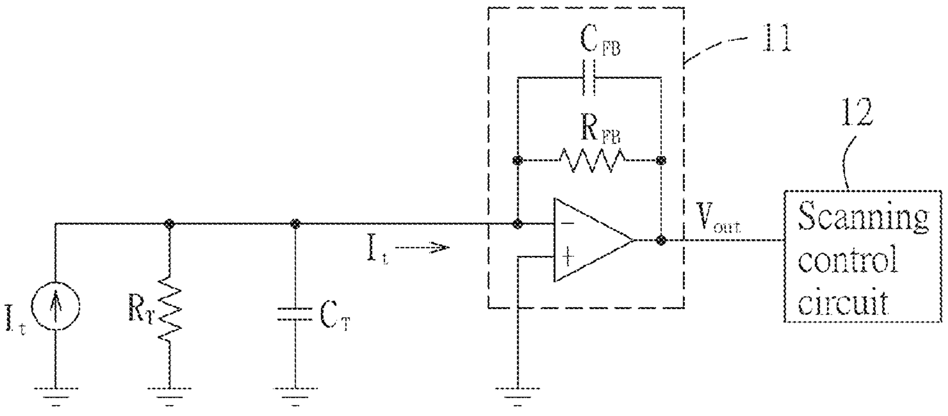


FIG.3
PRIOR ART

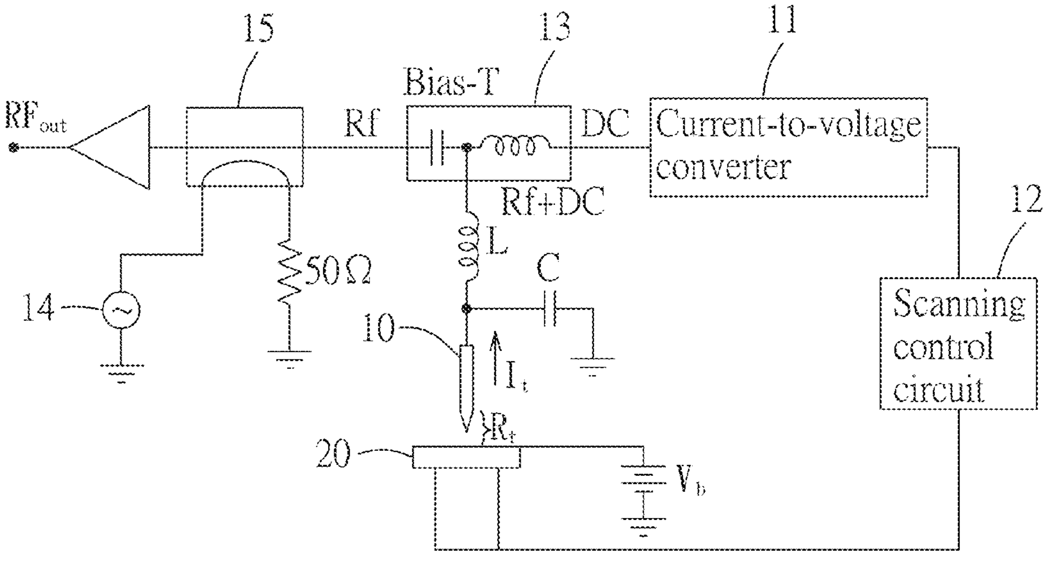


FIG.4
PRIOR ART

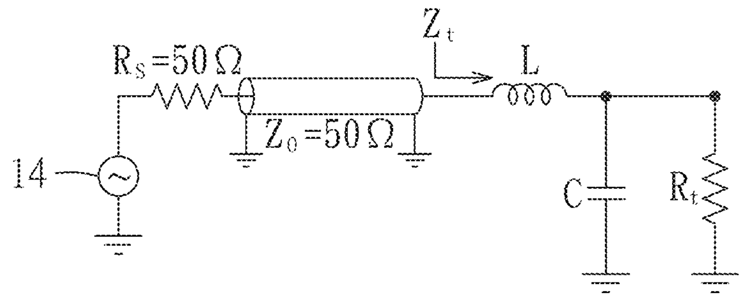


FIG.5
PRIOR ART

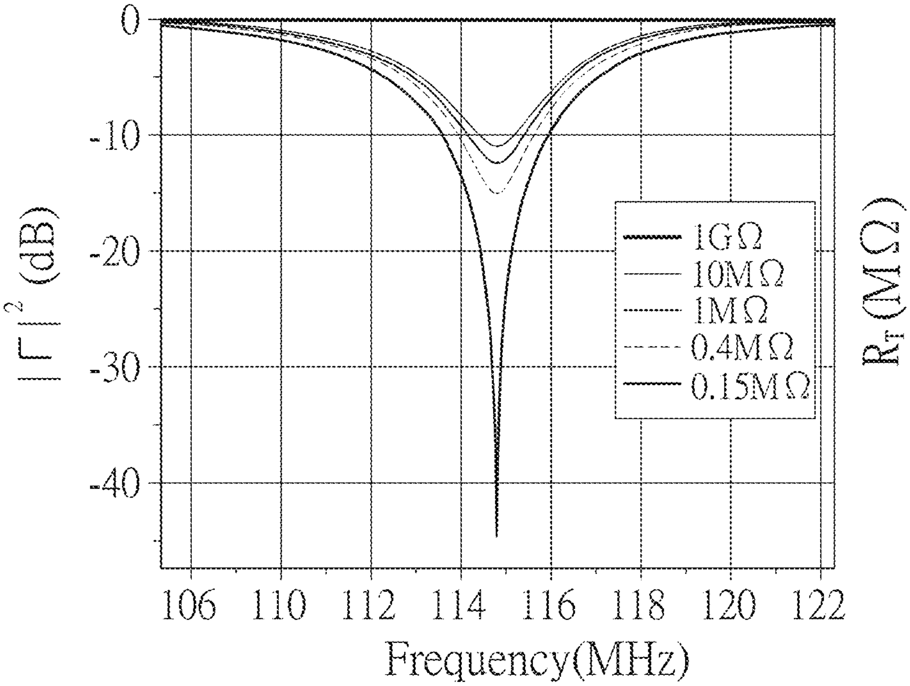


FIG.6
PRIOR ART

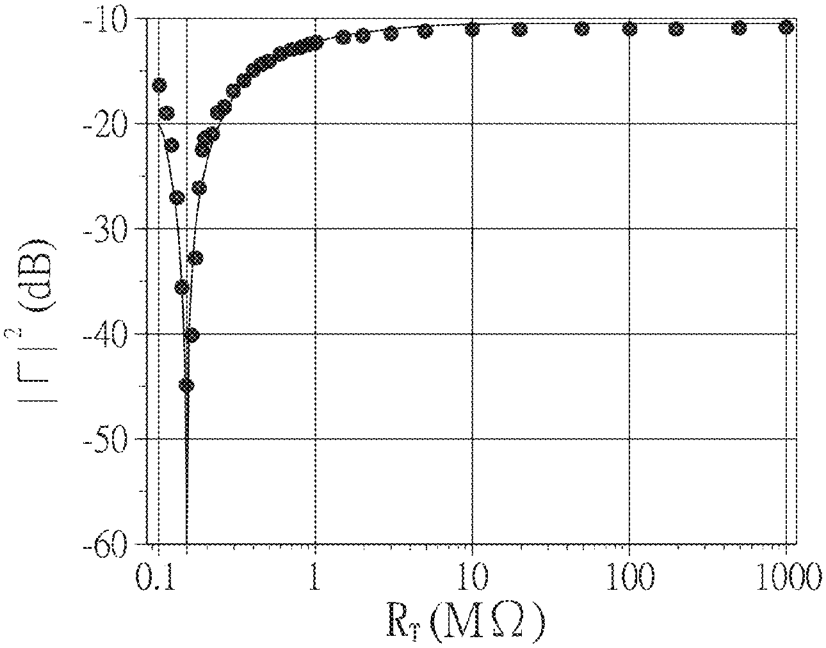


FIG.7
PRIOR ART

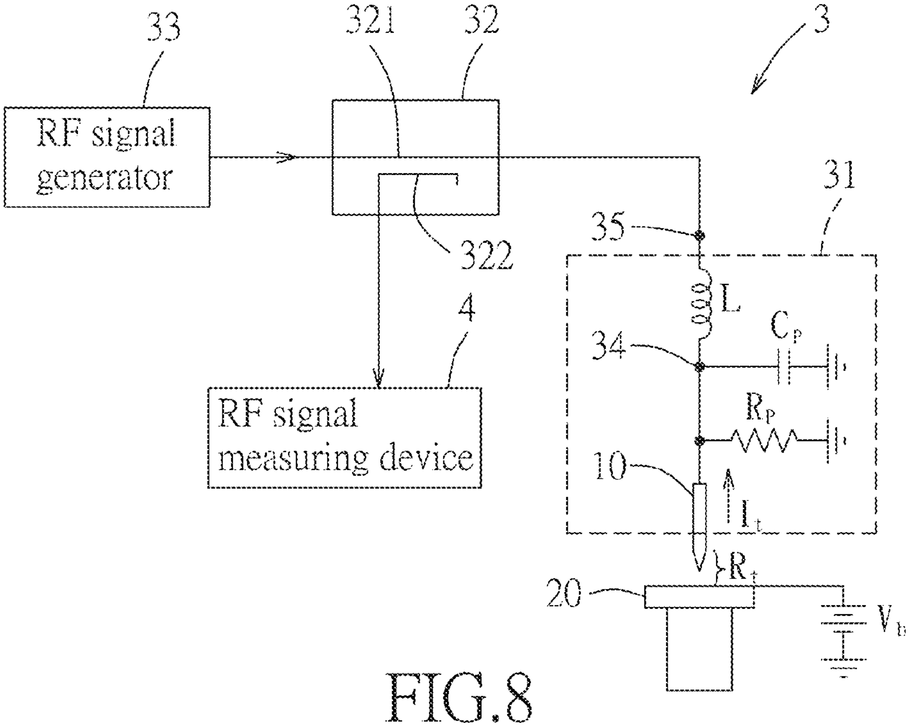


FIG.8

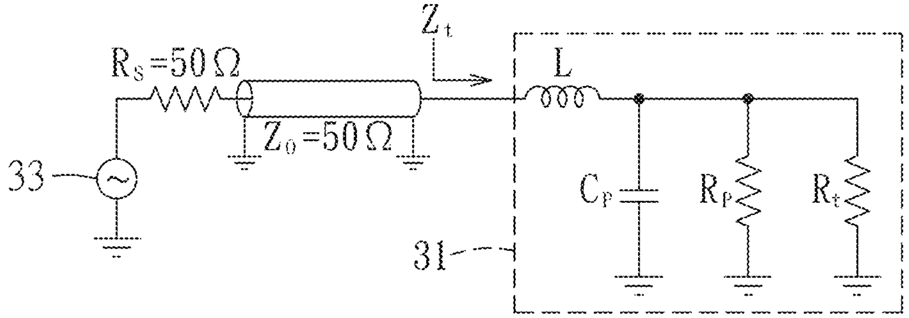

Z_t
L
R_S=50Ω
Z_0=50Ω
33
C_P
R_P
R_t
31

FIG.9

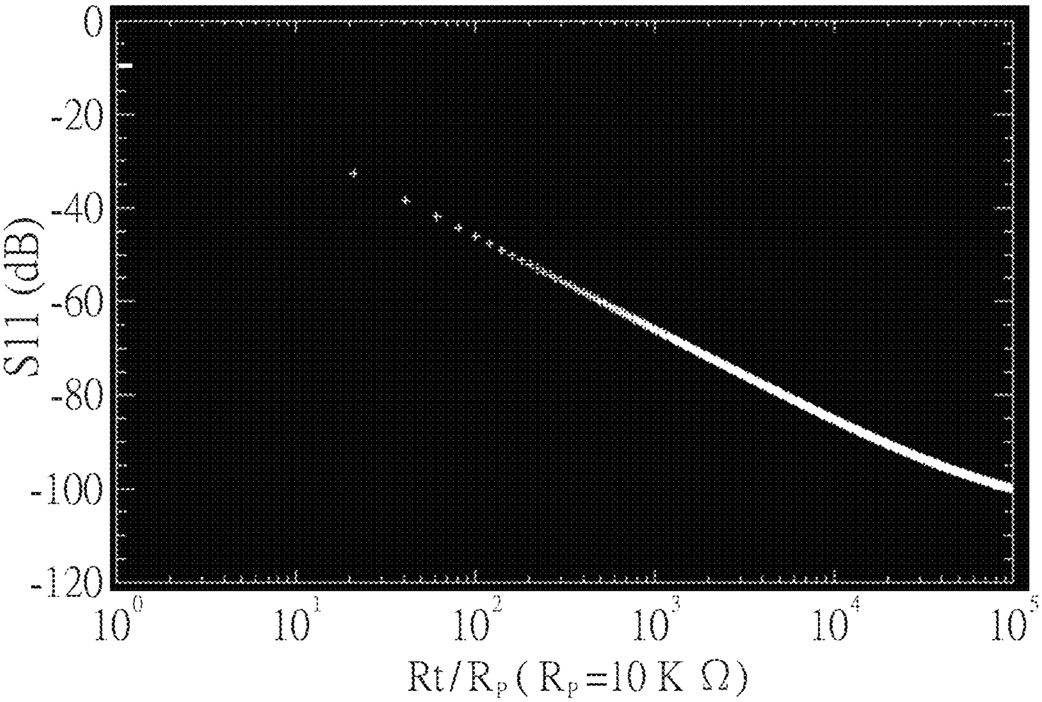
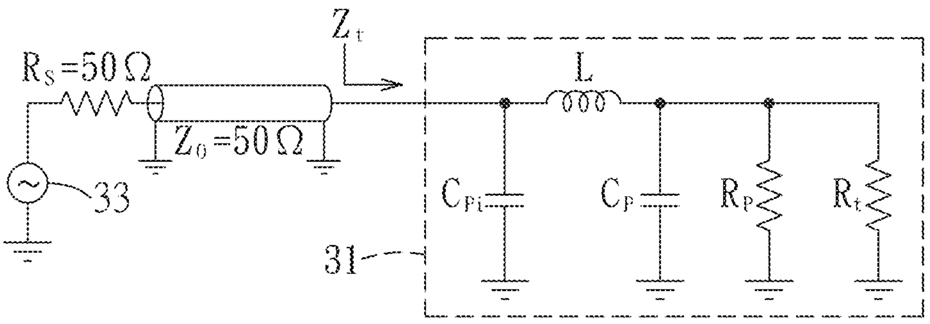
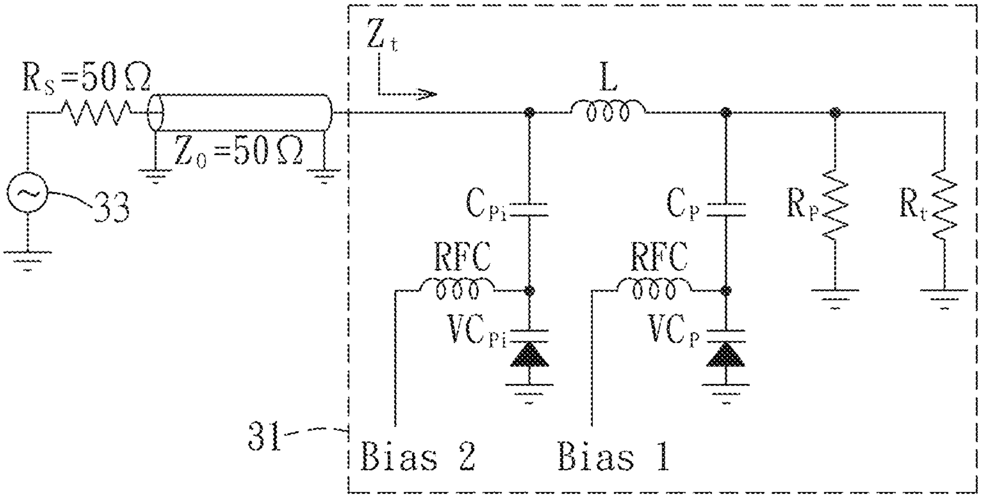

S11 (dB)
0
-20
-40
-60
-80
-100
-120
10^0
10^1
10^2
10^3
10^4
10^5
Rt/R_p (R_p=10 K Ω)

FIG.10



Z_t
$R_S=50\Omega$
L
$Z_0=50\Omega$
33
C_{Pi}
C_P
R_P
R_t
31

FIG.11



Z_t
$R_S=50\Omega$
L
$Z_0=50\Omega$
33
C_{Pi}
C_P
R_P
R_t
RFC
RFC
VC_{Pi}
VC_P
31
Bias 2
Bias 1

FIG.12

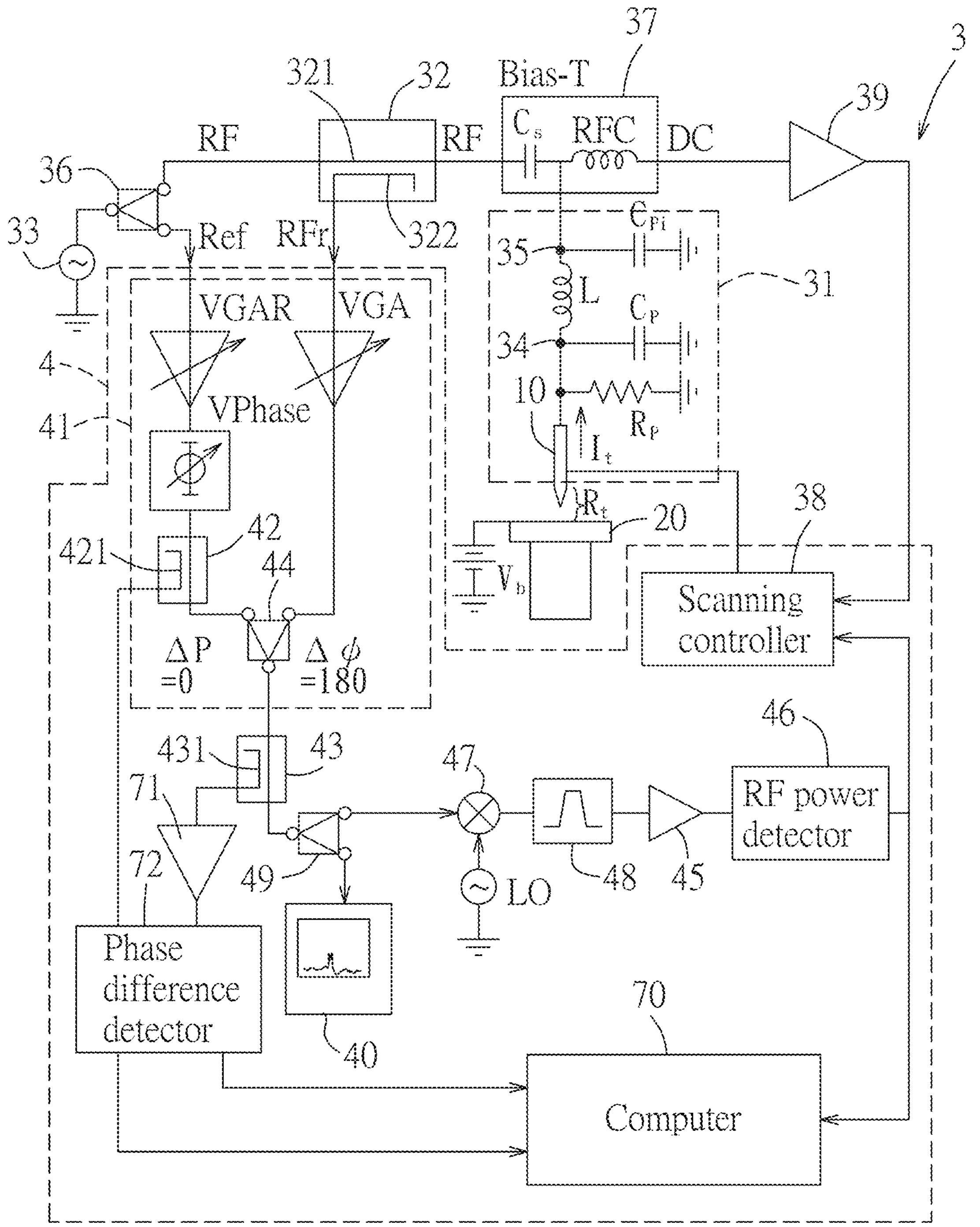

37
3
321
32
Bias-T
39
RF
RF
C_s
RFC
DC
36
33
Ref
RFr
322
C_{Pi}
35
L
31
VGAR
VGA
C_P
34
4
10
VPhase
41
R_P
I_t
R_t
20
38
42
421
44
V_b
Scanning controller
ΔP =0
Δ ϕ =180
46
431
43
47
71
RF power detector
72
49
LO
48
45
Phase difference detector
70
40
Computer

FIG.13

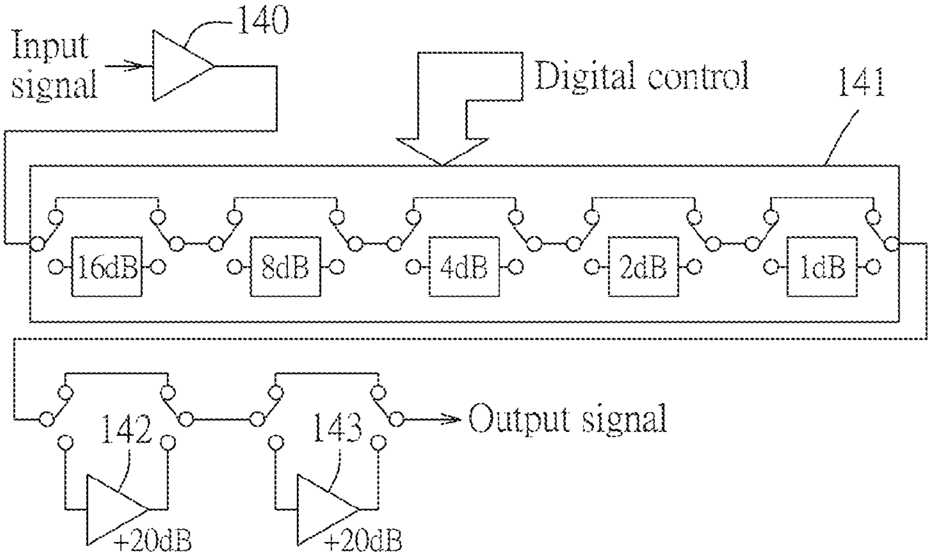

140
Input signal
Digital control
141
16dB
8dB
4dB
2dB
1dB
142
143
+20dB
+20dB
Output signal

FIG.14

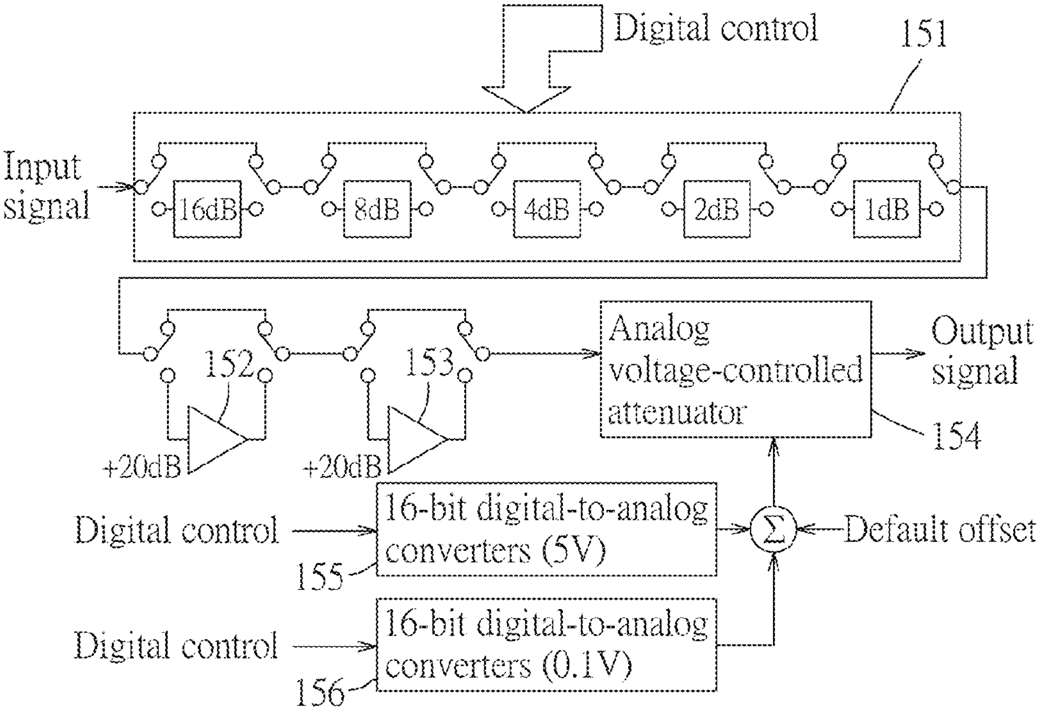

Digital control
151
Input signal
16dB
8dB
4dB
2dB
1dB
152
153
+20dB
+20dB
Analog voltage-controlled attenuator
Output signal
154
Digital control
16-bit digital-to-analog converters (5V)
155
Σ
Default offset
Digital control
16-bit digital-to-analog converters (0.1V)
156

FIG.15

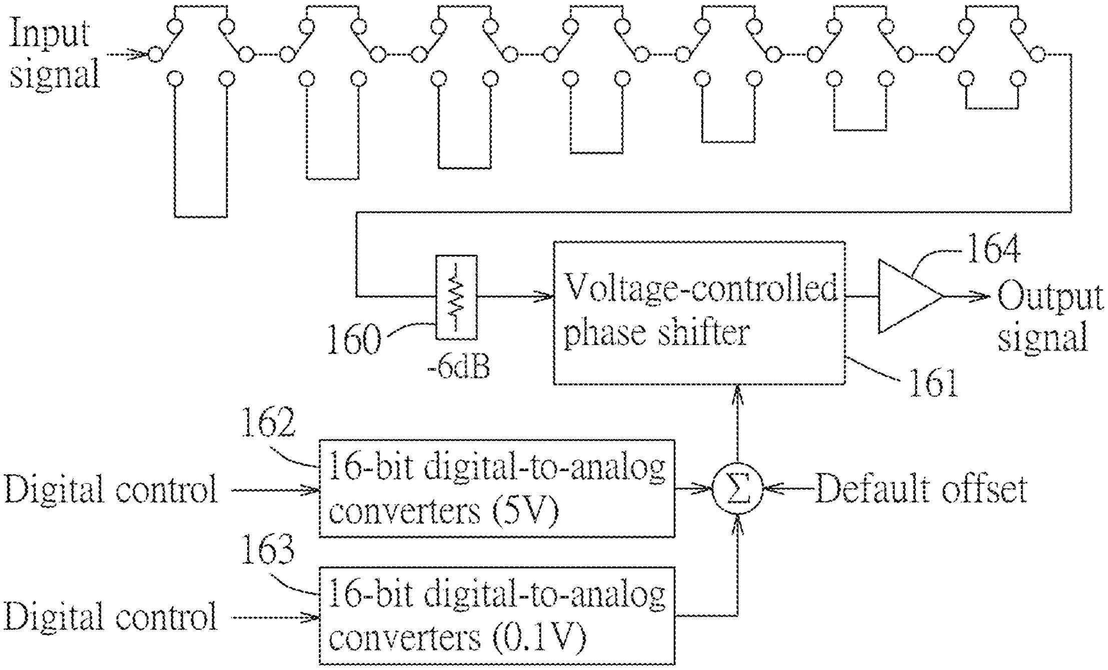

Input signal
160
-6dB
Voltage-controlled phase shifter
164
Output signal
161
162
Digital control
16-bit digital-to-analog converters (5V)
Σ
Default offset
163
Digital control
16-bit digital-to-analog converters (0.1V)

FIG.16

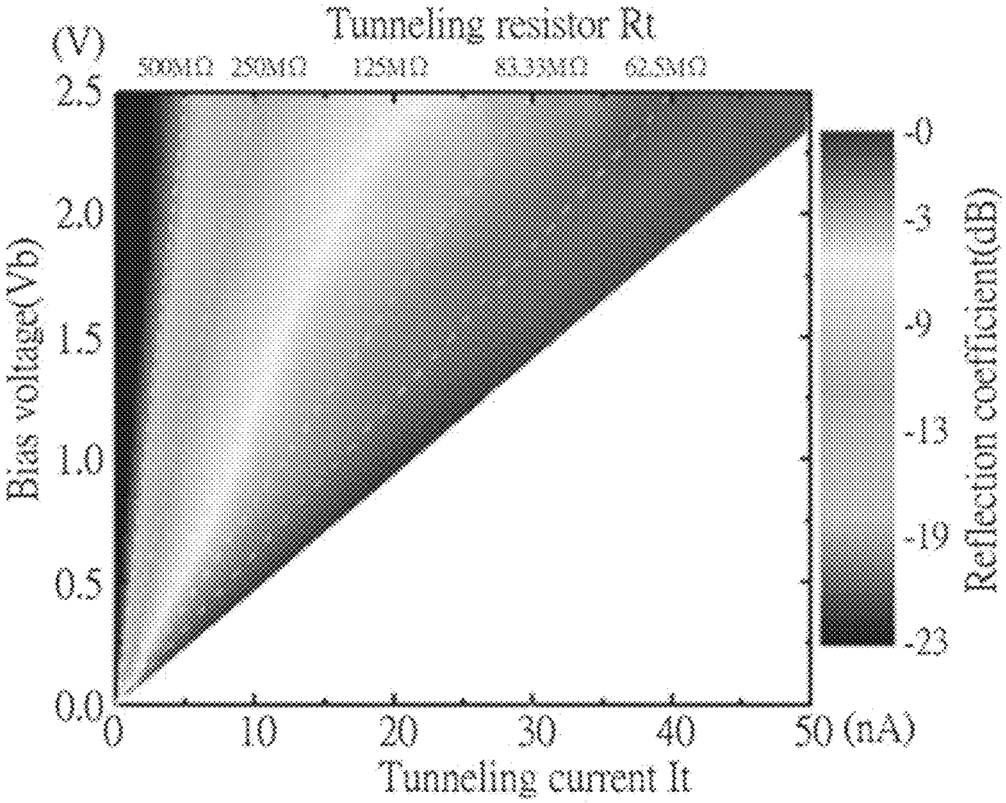

Tunneling resistor Rt
(V)
500MΩ
250MΩ
125MΩ
83.33MΩ
62.5MΩ
2.5
2.0
1.5
1.0
0.5
0.0
Bias voltage(Vb)
0
10
20
30
40
50 (nA)
Tunneling current It
-0
-3
-9
-13
-19
-23
Reflection coefficient(dB)

FIG.17

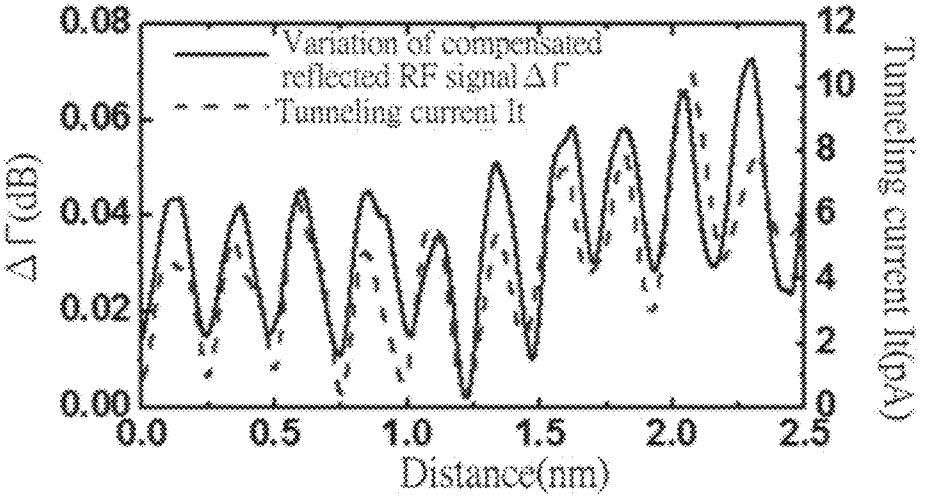

0.08
0.06
0.04
0.02
0.00
ΔΓ (dB)
Variation of compensated reflected RF signal ΔΓ
Tunneling current It
12
10
8
6
4
2
0
Tunneling current It(pA)
0.0
0.5
1.0
1.5
2.0
2.5
Distance(nm)

FIG.18

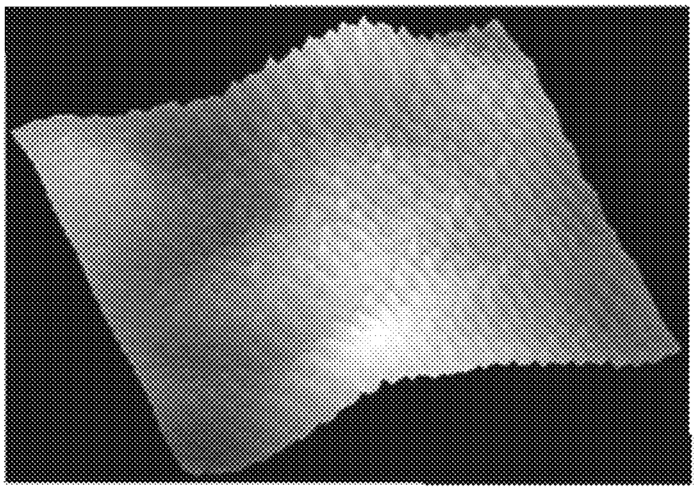


FIG.19

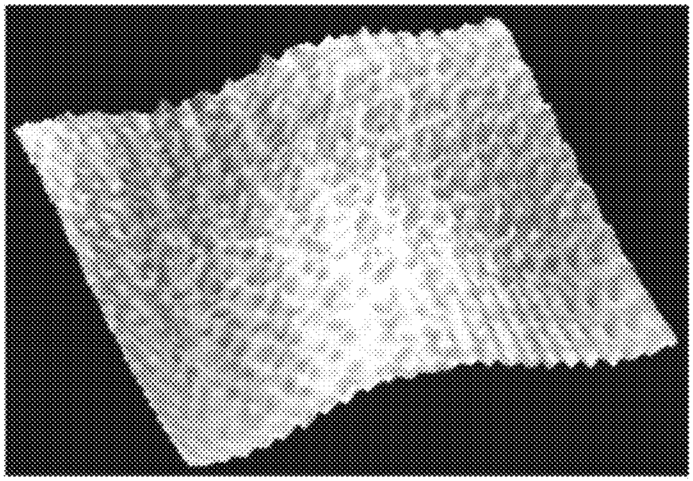


FIG.20

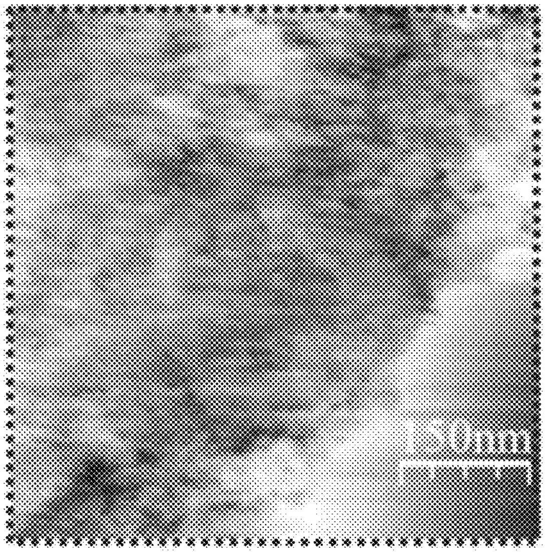


FIG.21

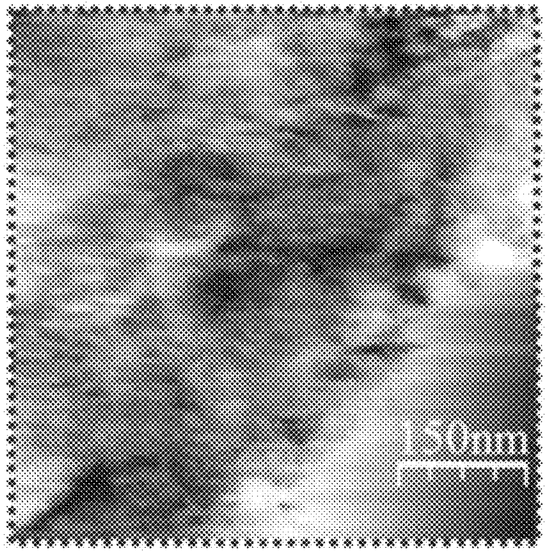


FIG.22

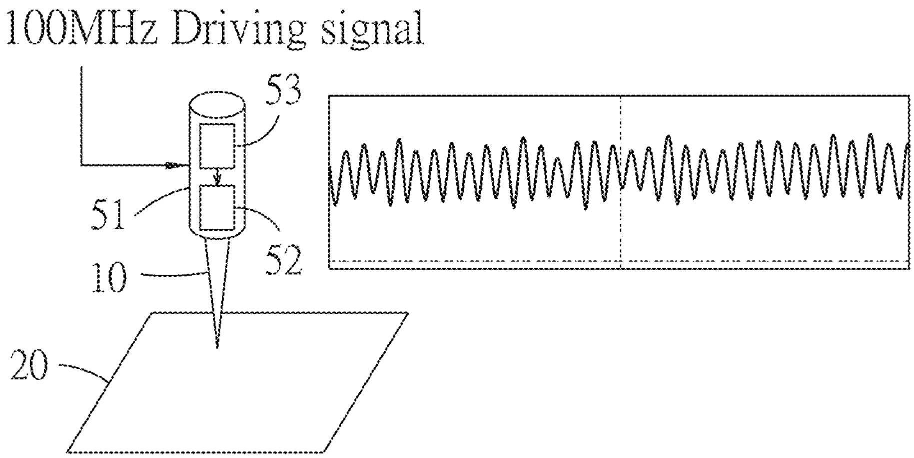

100MHz Driving signal
53
51
52
10
20

FIG.23

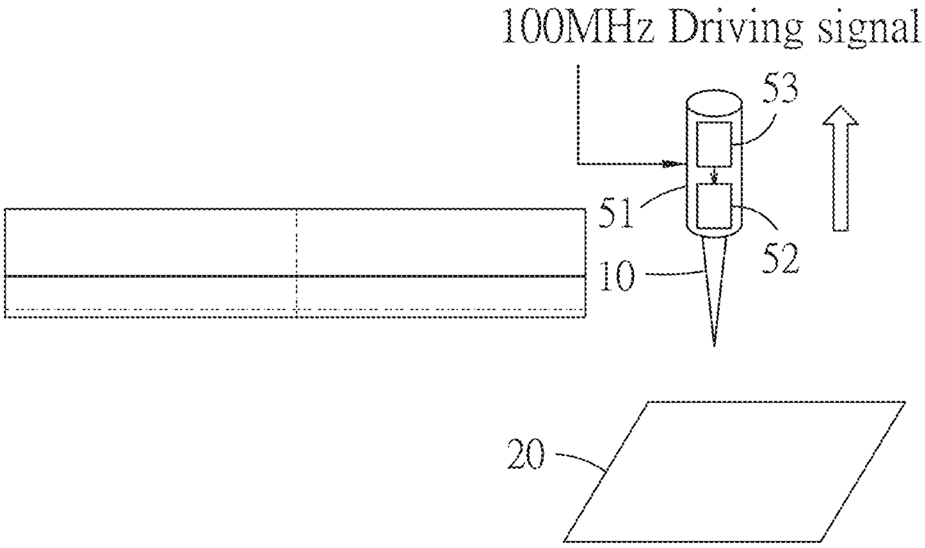

100MHz Driving signal
53
51
52
10
20

FIG.24

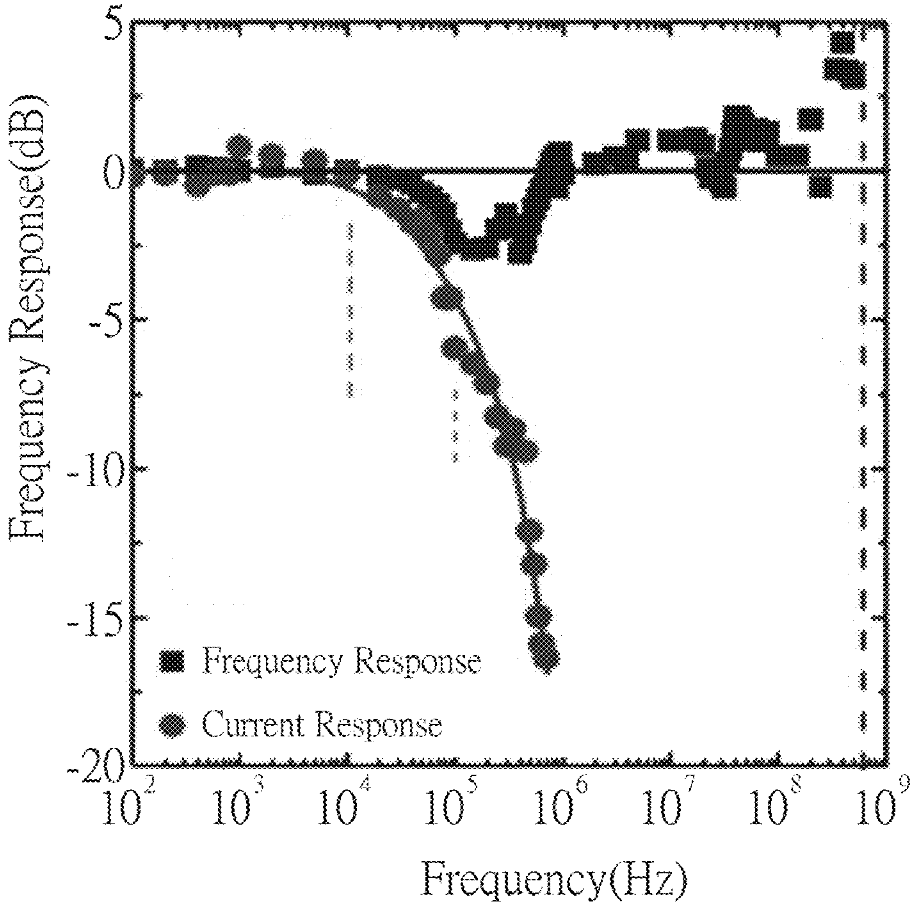

Frequency Response(dB)
5
0
-5
-10
-15
-20
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Frequency(Hz)
■ Frequency Response
● Current Response

FIG.25

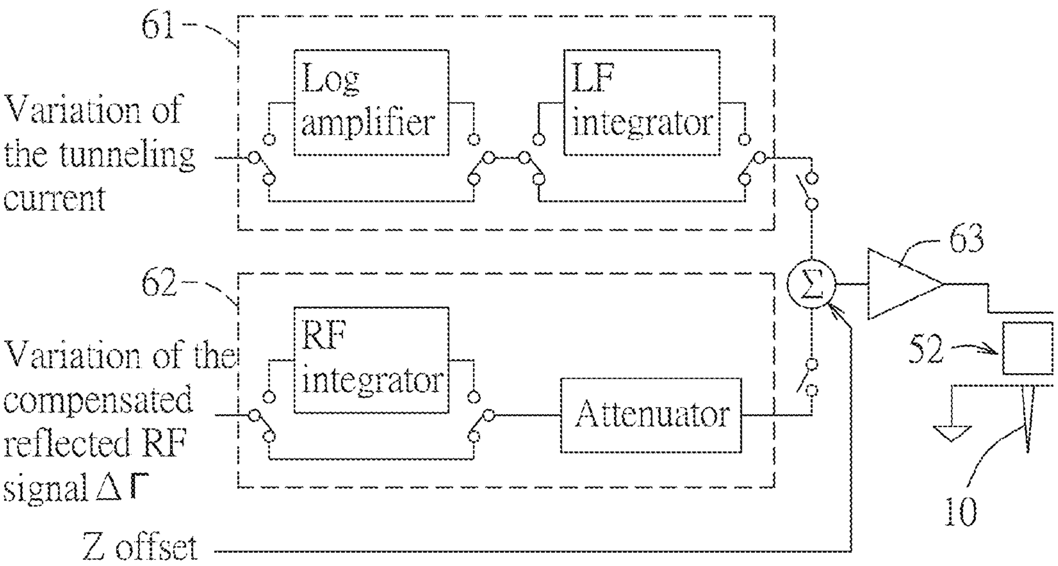

61
Log amplifier
LF integrator
Variation of the tunneling current
62
RF integrator
Attenuator
Variation of the compensated reflected RF signal ΔΓ
Z offset
Σ
63
52
10

FIG.26

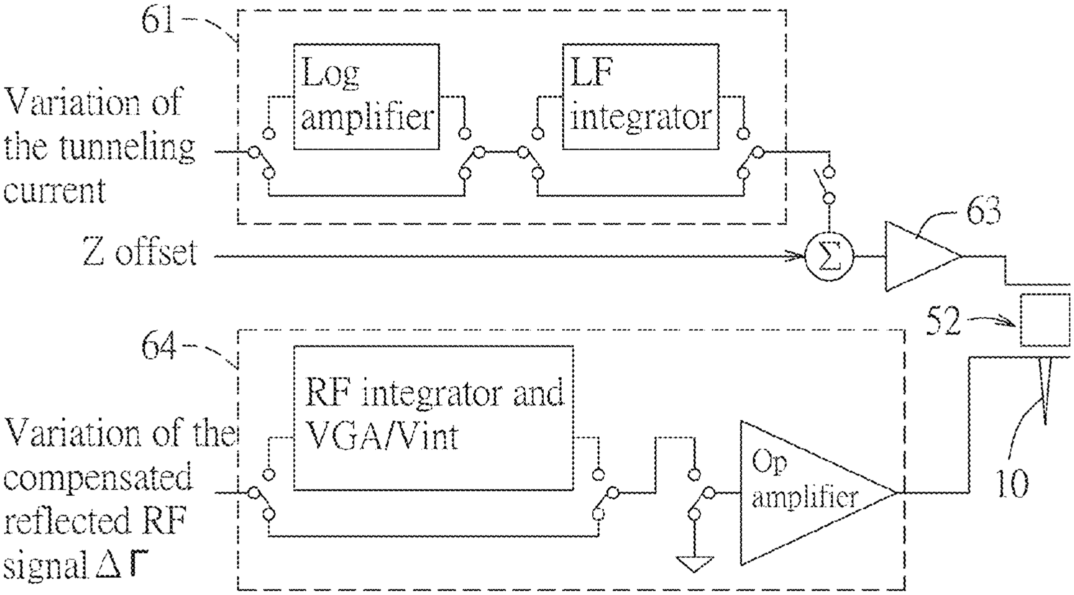

61
Log amplifier
LF integrator
Variation of the tunneling current
Z offset
Σ
63
52
64
RF integrator and VGA/Vint
Op amplifier
Variation of the compensated reflected RF signal ΔΓ
10

FIG.27

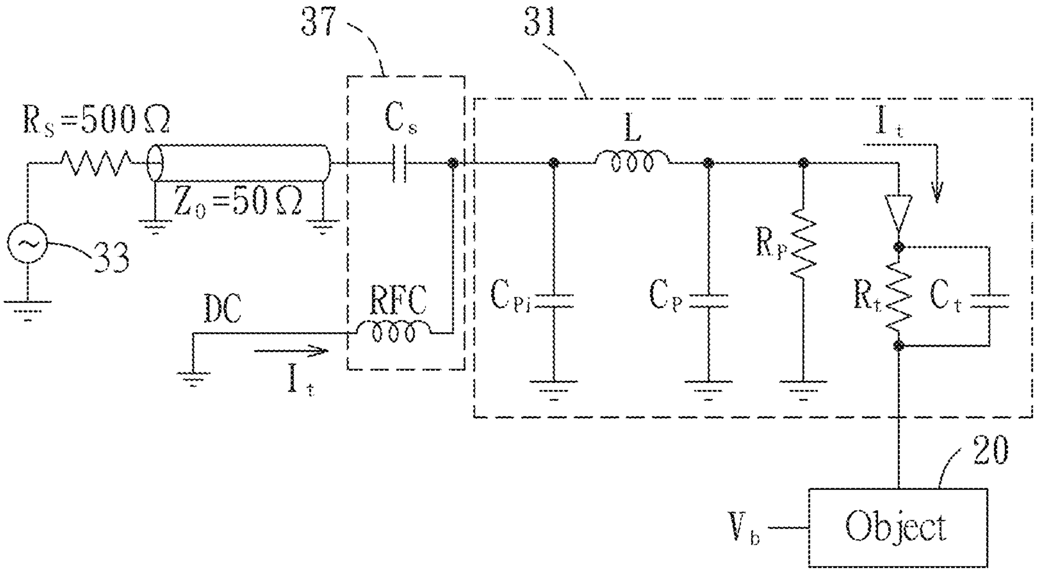

37
31
R_S=500Ω
C_s
L
I_t
Z_0=50Ω
33
R_P
C_{Pi}
C_P
R_t
C_t
DC
RFC
I_t
20
V_b
Object

FIG.28

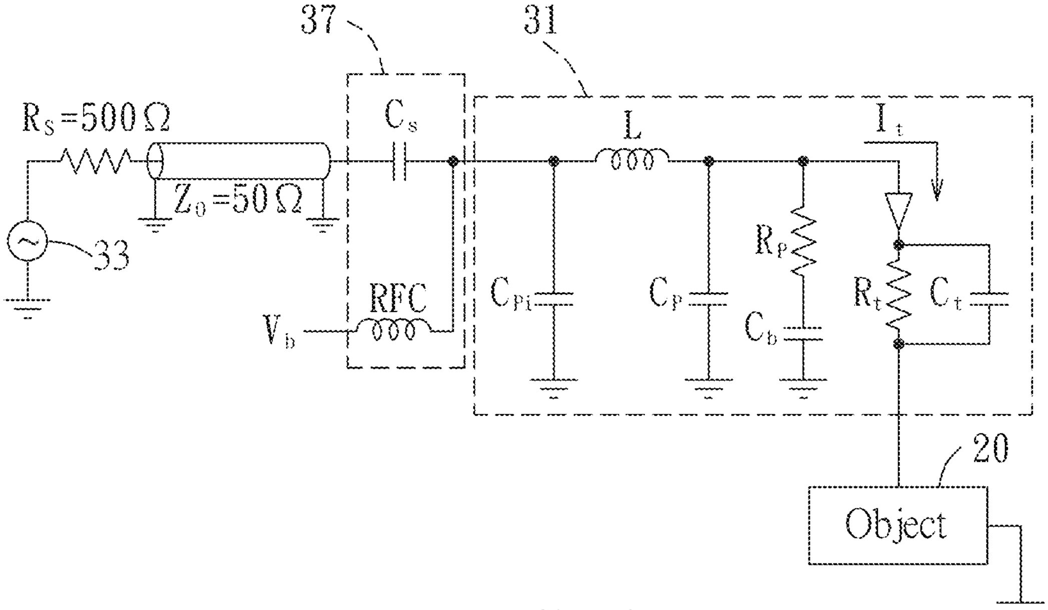

37
31
R_S=500Ω
C_s
L
I_t
Z_0=50Ω
33
R_P
C_{Pi}
C_P
R_t
C_t
C_b
RFC
V_b
20
Object

FIG.29

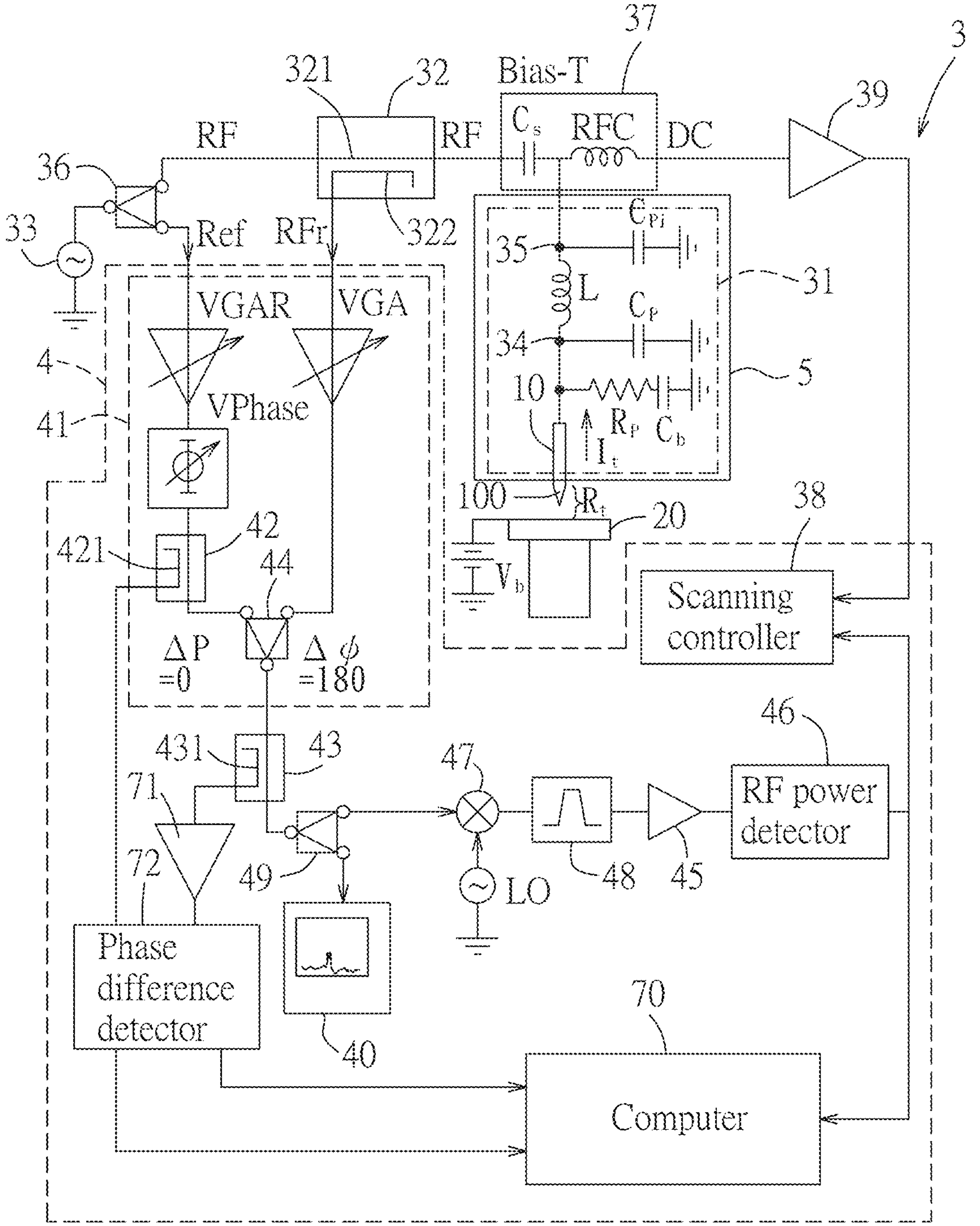

37
3
321
32
Bias-T
39
RF
RF
C_s
RFC
DC
36
33
Ref
RFr
322
C_{Pi}
35
31
L
VGAR
VGA
C_P
34
4
5
10
VPhase
41
R_P
C_b
I_t
100
R_t
20
38
42
421
44
V_b
Scanning controller
ΔP =0
Δ ϕ =180
46
431
43
47
71
RF power detector
72
49
LO
48
45
Phase difference detector
40
70
Computer

FIG.30

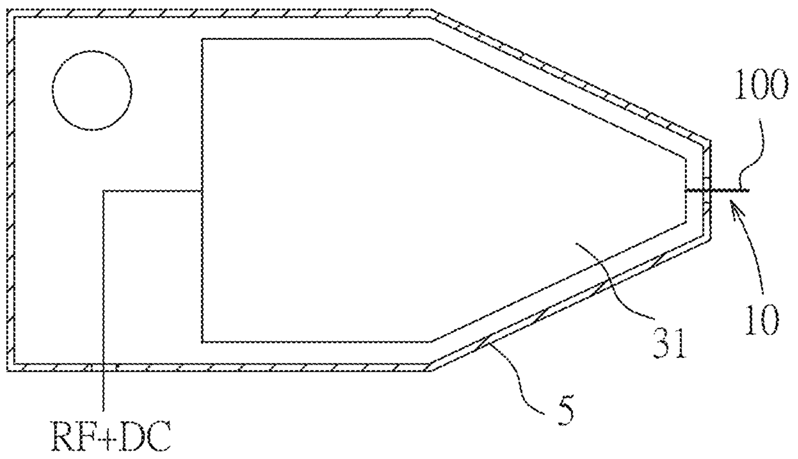

100
10
31
5
RF+DC

FIG.31

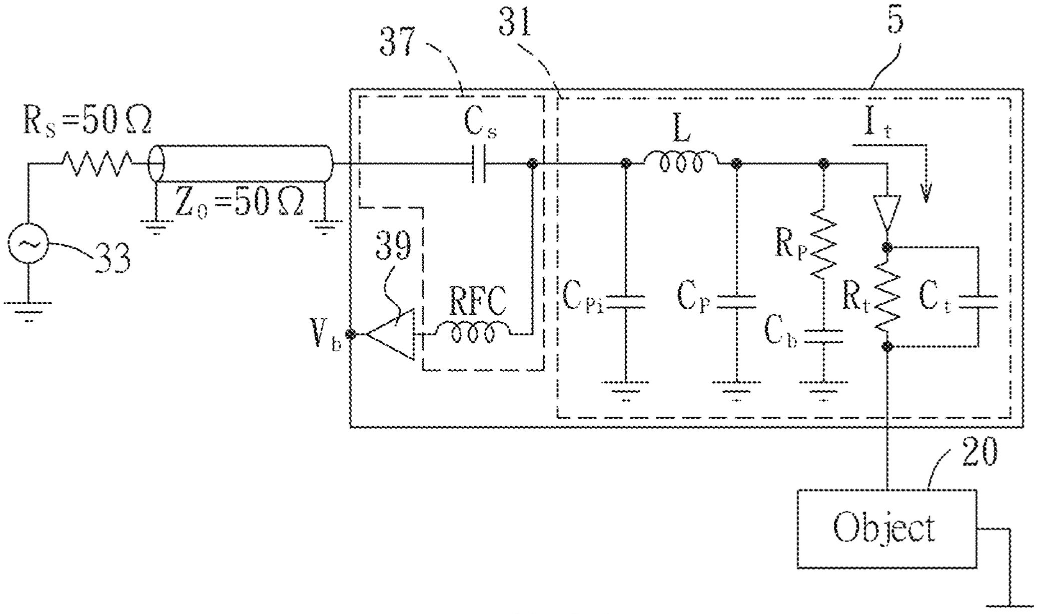

37
31
5
R_S=50Ω
Z_0=50Ω
33
C_s
39
RFC
V_b
L
I_t
C_{P1}
C_P
R_P
C_b
R_t
C_t
20
Object

FIG.32

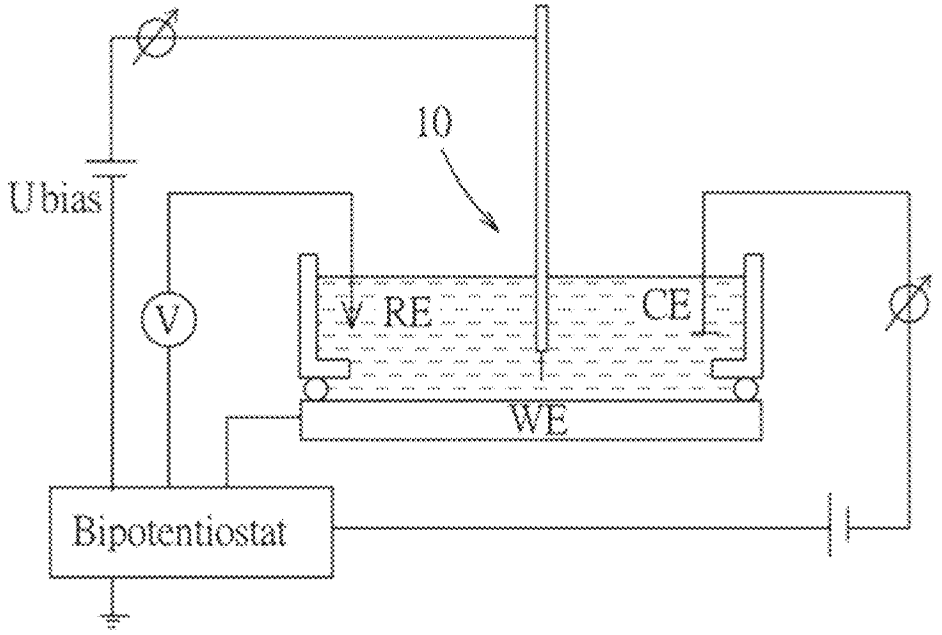

10
U bias
V
V
RE
CE
WE
Bipotentiostat

FIG.33

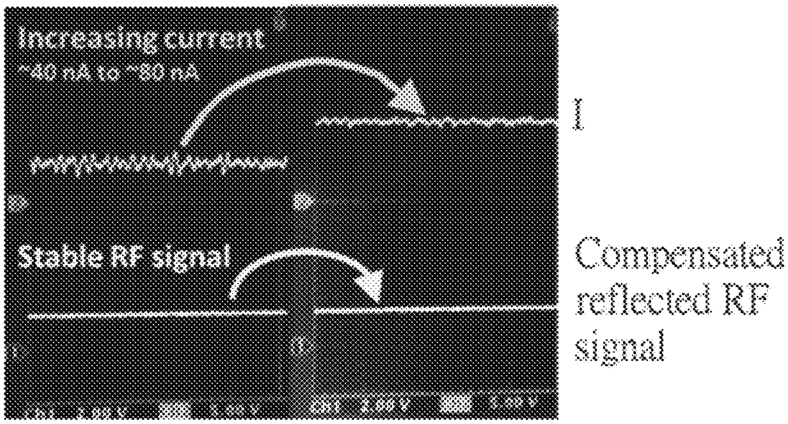

Increasing current
~40 nA to ~80 nA
I
Stable RF signal
Compensated reflected RF signal

FIG.34

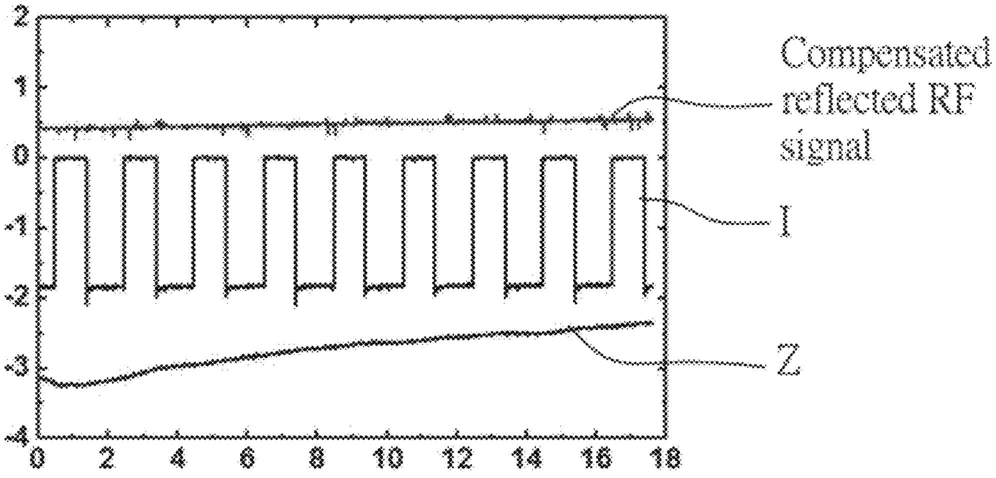


FIG.35(a)

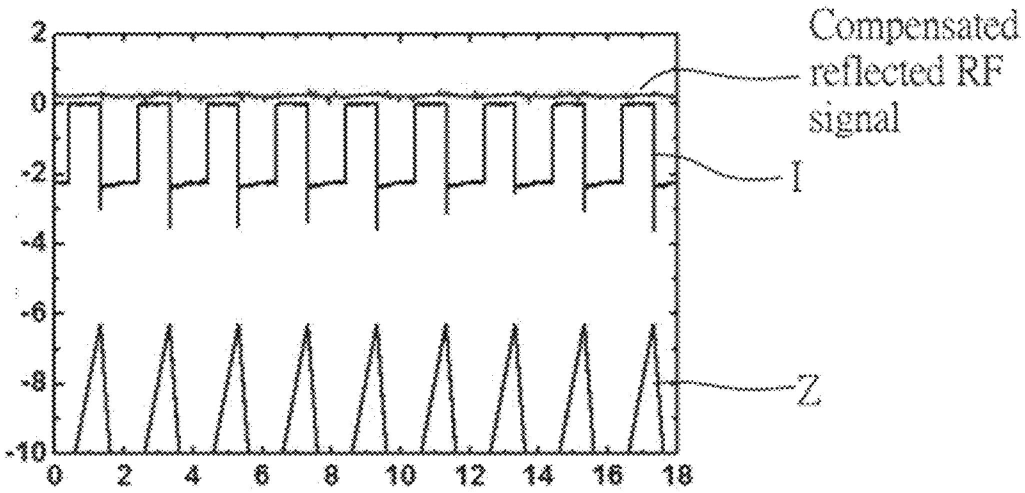


FIG.35(b)

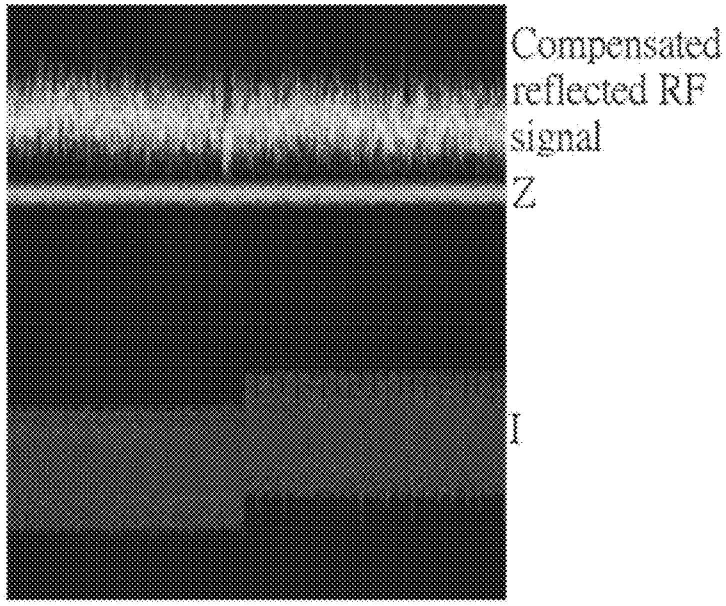


FIG.36(a)

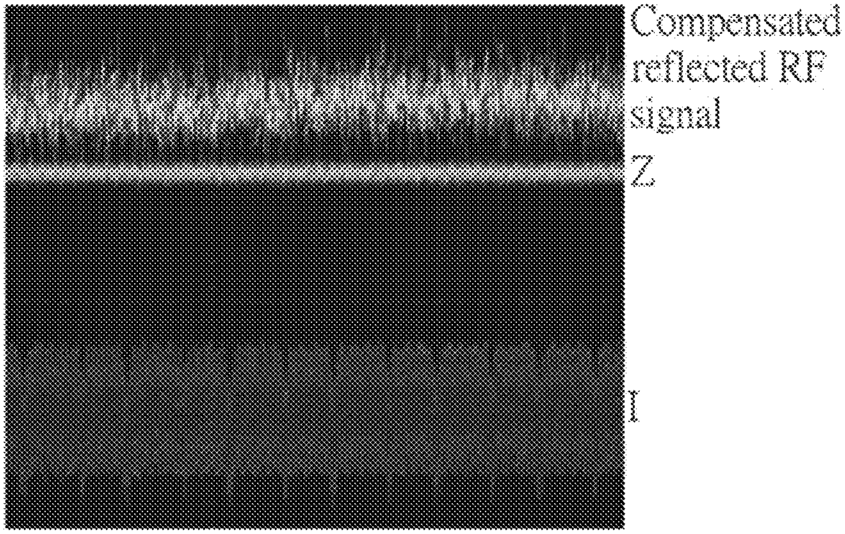


FIG.36(b)

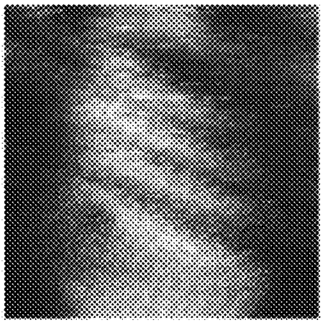


FIG.37(a)

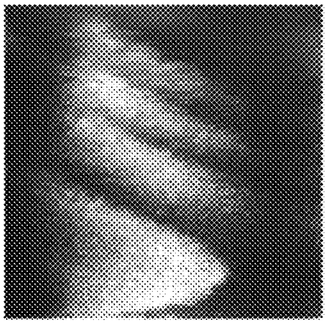


FIG.37(b)

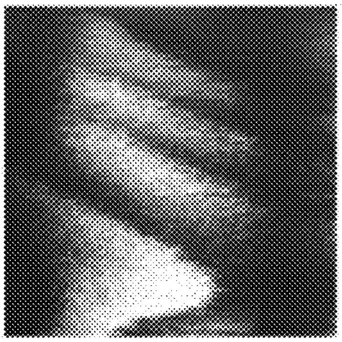


FIG.37(c)

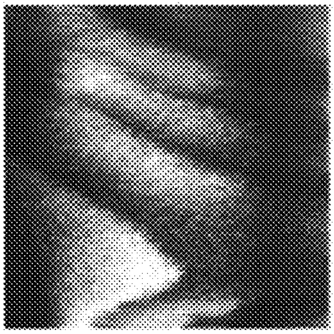


FIG.37(d)

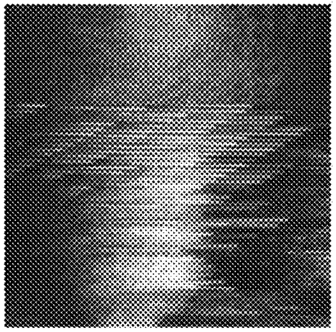


FIG.37(e)

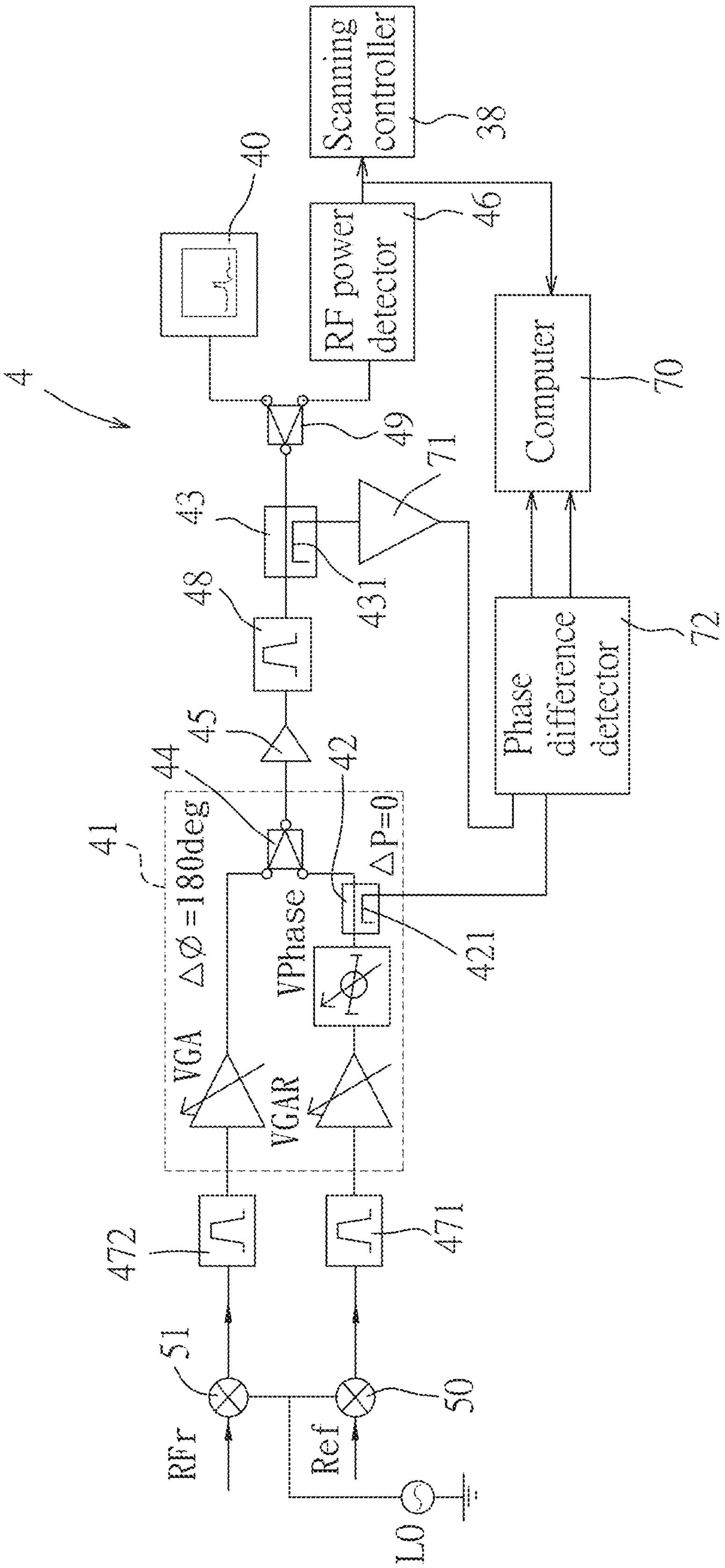

4
Scanning controller
38
40
RF power detector
46
Computer
70
49
43
71
431
48
Phase difference detector
72
45
44
42
41
ΔØ=180deg
ΔP=0
VPhase
421
VGA
VGAR
472
471
51
50
RFr
Ref
LO

FIG.38

RADIO-FREQUENCY REFLECTOMETRY SCANNING TUNNELING MICROSCOPE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority of Taiwanese Patent Application No. 103124553, filed on Jul. 17, 2014, and is a Continuation-in-Part of U.S. patent application Ser. No. 14/037,024 which is filed on Sep. 25, 2013 and which claims Taiwanese Patent Application No. 102125746, filed on Jul. 18, 2013.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to a tunneling microscope, more particularly to a radio-frequency reflectometry scanning tunneling microscope.

2. Description of the Related Art

There are two kinds of scanning operations of a conventional tunneling microscope, i.e., a constant height mode which is illustrated in FIG. **1**, and a constant current mode which is illustrated in FIG. **2**.

Referring to FIG. **3**, a current-to-voltage converter **11** adopted in the conventional tunneling microscope is illustrated. The current-to-voltage converter **11** amplifies and converts the tunneling current I_t into a voltage V_{out}, and outputs the voltage V_{out} to the scanning control circuit **12**. The scanning control circuit **12** controls the altitude of the probe based on the voltage V_{out}. A gain of the current-to-voltage converter **11** is decided by a feedback resistor R_{FB} therein. Since the amplitude of the tunneling current I_t is very small (pico-amp to nano-amp scale), in practice, the feedback resistor R_{FB} is set at 100 M Ohms or larger. Moreover, since an intrinsic capacitor C_{FB} of the current-to-voltage converter **11** is usually of picofarad scale, a time constant $R_{FB}\times C_{FB}$ attributed to the feedback resistor R_{FB} and the intrinsic capacitor C_{FB} limits a frequency of the voltage V_{out} to about tens of kilohertz, such that the current-to-voltage converter **11** is limited to operate at no more than hundreds of kilohertz. This limitation causes the conventional tunneling microscope to be suitable only for observing physical and chemical phenomena that are static or dynamic but with relatively slow evolution.

Moreover, the conventional tunneling microscope is limited to the following conditions when in use. First, the object **20** to be scanned is required to be an electrically conductive material. Second, the conventional tunneling microscope which is operating in the constant current mode is vulnerable to interference resulting from different kinds of external electron/current sources. The external electron/current sources are selected from the group consisting of incident electrons emitted by an electron gun, secondary electrons, Auger electrons, photoelectrons excited by radiation, ionic current, and combinations thereof. If an external current resulting from the electron/current sources enters or passes by a vicinity of a tunneling barrier, the external current resulting from the electron/current sources together with the tunneling current I_t would be amplified by the current-to-voltage converter **11**, thereby adversely influencing the aforementioned feedback control mechanism, so that the scanning result of the surface of the object **20** may not be obtained properly.

Accordingly, in order to overcome the aforementioned issue that the operating bandwidth of the tunneling microscope is limited, a radio-frequency (RF) scanning tunneling microscope has been proposed by Kemiktarak et al., and a circuit diagram thereof is illustrated in FIG. **4**. Referring to FIG. **4**, a right-hand side of a circuit of the RF scanning tunneling microscope shows that a similar circuit structure of the conventional tunneling microscope is adopted. That is to say, the tunneling current I_t generated between the probe **10** and the object **20** is outputted, via an inductor L having one end coupled electrically to the probe **10** and via a bias tee circuit **13** coupled electrically to another end of the inductor L, to the current-to-voltage converter **11**. The current-to-voltage converter **11** amplifies and converts the tunneling current I_t, and then outputs the tunneling current I_t thus amplified and converted to the scanning control circuit **12**, so as to control the altitude of the probe **10**. The scanning control circuit **12** further depicts the surface of the object **20** based on the tunneling current I_t outputted by the current-to-voltage converter **11**. In addition, a left-hand side of the circuit of the RF scanning tunneling microscope is an RF scanning circuit. A grounding capacitor C is coupled electrically to said one end of the inductor L. The RF scanning circuit includes an RF source **14** outputting an RF signal via a directional coupler **15**, via the bias tee circuit **13** that has two ports passing RF signals bi-directionally and a third port passing DC signal, and via the inductor L to the probe **10**. The probe **10** cooperates with the object **20** to form a tunneling resistor R_t therebetween, such that the inductor L is connected in series with a parallel connection of the tunneling resistor R_t and the capacitor C, so as to form an L-leg low pass LCR resonant circuit. An equivalent circuit of the L-leg low pass LCR resonant circuit is illustrated in FIG. **5**, and a resonant frequency thereof is defined by

$$\omega_{LC} = \sqrt{\frac{1}{LC}\left(1 - \frac{L}{CR_t^2}\right)},$$

where ω_{LC} represents an angular frequency associated with the resonant frequency, L represents inductance of the inductor L, C represents capacitance of the capacitor C, and R_t represents resistance of the tunneling resistor R_t, i.e., a tunneling barrier.

It is evident from the abovementioned function that the resonant frequency is substantially determined after the inductance of the inductor L and the capacitance of the capacitor C have been decided. Resistance of the tunneling resistor R_t is adjusted according to

$$R_t \approx \frac{L}{C\times Z_o},$$

where Z_o represents output impedance of the RF scanning circuit that outputs the RF signal to the L-leg low pass LCR resonant circuit, such that impedance Z_t of the L-leg low pass LCR resonant circuit corresponds to the output impedance Z_o, so as to achieve optimum impedance matching. At this time, the L-leg low pass LCR resonant circuit may obtain substantially the maximum power of the RF signal (i.e., maximum power transfer).

Referring to FIG. **6**, when the resistance of the tunneling resistor R_t is adjusted to 0.15M Ohms, a relatively good impedance matching may be achieved, and return loss is 45 dB. If the probe **10** is moved away from the object **20** along the Z-axis, resistance of the tunneling resistor R_t increases. At the same time, since the impedance Z_t of the L-leg low pass LCR resonant circuit does not match with the output impedance Z_O, power of a reflected RF signal resulting from reflection of the RF signal by the L-leg low pass LCR resonant circuit also increases. FIG. **6** illustrates the phenomena where a reflection coefficient for the L-leg low pass LCR resonant circuit increases rapidly (i.e., the return loss decreases) while the resistance of the tunneling resistor R_t increases. Further, it is evident from FIG. **6** that when the resistance of the tunneling resistor R_t changes from 0.15M ohms to 0.4M ohms, the return loss changes from 45 db to 15 dB. When the resistance of the tunneling resistor R_t is equal to 1M ohms, the return loss is 12 dB. When the resistance of the tunneling resistor R_t ranges from 10M ohms to 1G ohms, the return loss is kept at around 11 dB, and variation of the return loss is so subtle that, in practice, it is hard to distinguish the differences between the return loss while the resistance of the tunneling resistor R_t is set at around 10M ohms and at around 100M ohms. Moreover, in practical applications, the resistance of the tunneling resistor R_t usually ranges from 10M ohms to 1 G ohms, so that the return loss is hardly utilized for obtaining actual resistance of the tunneling resistor R_t by means of the aforementioned RF scanning tunneling microscope.

It is evident from FIG. **7** that a relationship between the return loss and the resistance of the tunneling resistor R_t is a non-monotonic function. That is, the same return loss may correspond to two different resistances of the tunneling resistor R_t. The non-monotonic relationship may cause misjudgment of the scanning result made by the scanning control circuit **12**, and instability may arise when control of the altitude of the probe **10** is based on the return loss.

SUMMARY OF THE INVENTION

Therefore, an object of the present invention is to provide a radio-frequency (RF) reflectometry scanning tunneling microscope which provides a monotonic relationship between magnitude of a reflection coefficient and resistance of a tunneling resistor, and which is capable of operating in a relatively high frequency band compared to the conventional tunneling microscope and is capable of operating in a condition corresponding to a usual resistance range of the tunneling resistor (i.e., 10M ohms to 1 G ohms).

Accordingly, the RF reflectometry scanning tunneling microscope of this invention is suitable for observing a surface of an object, and comprises a probe, an RF resonant circuit, a directional coupler, and an RF signal measuring device. The probe is adapted to be positioned relative to the surface of the object, and to interact with the object to forma tunneling resistor therebetween. The RF resonant circuit includes an inductor that has a first end connected to the probe, a capacitor that is connected to the first end of the inductor, and a resistor that is connected in parallel with the capacitor. The RF resonant circuit is to cooperate with the tunneling resistor to form a LCR resonant circuit in which the inductor is connected to a parallel connection of a capacitor, a resistor and the tunneling resistor. The directional coupler is coupled electrically to a second end of the inductor of the RF resonant circuit, and is configured to receive an RF signal, to output the RF signal thus received to the LCR resonant circuit, and to receive a reflected RF signal that results from reflection of the RF signal by the LCR resonant circuit. The RF signal measuring device is adapted to receive the reflected RF signal from the LCR resonant circuit via the directional coupler, and is operable to generate a scanning result associated with the surface of the object based on the reflected RF signal.

The present invention, by utilizing the reflected RF signal, is capable of measuring the tunneling effect that occurs between the probe and the object. Moreover, the present invention is further capable of measuring the reactance effect on the surface of the object through the RF signal measuring device. In addition, the present invention may be alleviated from interference of external electron/current sources, so as to obtain a clear and uninfluenced scanning result of the surface of the object.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the present invention will become apparent in the following detailed description of three embodiments with reference to the accompanying drawings, of which:

FIG. **1** is a schematic diagram illustrating a conventional scanning tunneling microscope that operates in a constant height mode;

FIG. **2** is a schematic diagram illustrating the conventional scanning tunneling microscope that operates in a constant current mode;

FIG. **3** is a circuit diagram illustrating a current-to-voltage converter adopted in the conventional scanning tunneling microscope;

FIG. **4** is a circuit diagram illustrating a conventional radio-frequency (RF) scanning tunneling microscope;

FIG. **5** is a circuit diagram illustrating an equivalent circuit of an L-leg low pass LCR resonant circuit of the conventional RF scanning tunneling microscope;

FIG. **6** illustrates relationships between return loss and frequency corresponding to different resistances of a tunneling resistor;

FIG. **7** illustrates that a relationship between the return loss obtained by the conventional RF scanning tunneling microscope and the resistance of the tunneling resistor is a non-monotonic function;

FIG. **8** is a circuit diagram illustrating a LCR resonant circuit of a first embodiment of an RF scanning tunneling microscope according to the present invention;

FIG. **9** is a circuit diagram illustrating an equivalent circuit of the LCR resonant circuit of the first embodiment;

FIG. **10** is a log-log plot illustrating a relationship between the reflection coefficient and a division of the resistance of the tunneling resistor R_t by the resistance of the resistor R_p;

FIG. **11** is a circuit diagram illustrating that the RF resonant circuit further includes an auxiliary capacitor;

FIG. **12** is a circuit diagram illustrating that the RF resonant circuit further includes first and second voltage-controlled capacitors;

FIG. **13** is a circuit diagram illustrating the first embodiment of the RF reflectometry scanning tunneling microscope according to the present invention;

FIG. **14** is a circuit diagram illustrating a first voltage-controlled gain amplifier of the first embodiment;

FIG. **15** is a circuit diagram illustrating a second voltage-controlled gain amplifier of the first embodiment;

FIG. **16** is a circuit diagram illustrating a phase shifter of the first embodiment;

FIG. **17** illustrates a relationship among the reflection coefficient, resistance of the tunneling resistor, the tunneling current, and a bias voltage;

FIG. **18** illustrates a relationship between a variation of the compensated reflected RF signal and the tunneling current;

FIG. **19** is an RF scanning image illustrating a scanning result associated with a surface of an object;

FIG. **20** is a current scanning image illustrating the scanning result associated with the surface of the object;

FIG. **21** is an image of an area on the surface of the object obtained through the first embodiment which operates under a constant current mode;

FIG. **22** is an image of the same area on the surface of the object obtained through the first embodiment which operates under a constant RF reflection magnitude mode;

FIG. **23** is a schematic diagram illustrating that when the probe is sufficiently close to the object, magnitude of a compensated reflected RF signal varies in response to a driving signal inputted to the probe;

FIG. **24** is a schematic diagram illustrating that when the altitude of the probe with respect to the surface of the object is increased to an extent that the tunneling current disappears, the magnitude of the compensated reflected RF signal is kept fixed;

FIG. **25** is a frequency response of the first embodiment illustrating that a relatively wide detecting bandwidth is achieved;

FIG. **26** is a circuit block diagram illustrating a scanning controller in one configuration of the first embodiment;

FIG. **27** is a circuit block diagram illustrating the scanning controller in another configuration of the first embodiment;

FIG. **28** is a circuit diagram illustrating that a bias voltage is applied to the object and the probe is grounded;

FIG. **29** is a circuit diagram illustrating that the object is grounded, and the LCR resonant circuit is applied with a bias voltage; and

FIG. **30** is a circuit diagram illustrating a second embodiment of the RF reflectometry scanning tunneling microscope according to the present invention;

FIG. **31** is a schematic diagram illustrating a shielding casing of the second embodiment of the RF reflectometry scanning tunneling microscope according to the present invention;

FIG. **32** is a circuit diagram illustrating that the probe, the RF resonant circuit, a bias tee circuit, and a current-to-voltage converter are accommodated in the shielding casing of the second embodiment;

FIG. **33** is a schematic diagram illustrating that the probe of the second embodiment is used for observing a surface of an object that is immersed in a liquid-phase electrochemical reaction tank;

FIG. **34** illustrates that, in the second embodiment, the compensated reflected RF signal remains stable while an aggregated current is changing;

FIG. **35**(*a*) illustrates that the altitude of the probe with respect to the surface of the object does not change according to variation of the aggregated current when the second embodiment operates under the constant RF reflection magnitude mode;

FIG. **35**(*b*) illustrates that the altitude of the probe with respect to the surface of the object is significantly proportional to the integral of the aggregated current in the form of a square-wave when the second embodiment operates under the constant current mode;

FIG. **36**(*a*) illustrates variation of the aggregated current at the instant when an X-ray excitation source is activated in the second embodiment;

FIG. **36**(*b*) illustrates the variation of the aggregated current when the X-ray excitation source is switched alternately between an ON state and an OFF state in the second embodiment;

FIG. **37**(*a*) is an image of an area on the surface of the object obtained through the second embodiment which operates under the constant current mode without interference of an external current;

FIG. **37**(*b*) is an image of the area on the surface of the object obtained through the second embodiment which operates under the constant RF reflection magnitude mode with the presence of an external current;

FIG. **37**(*c*) is an image of an area on the surface of the object obtained through the second embodiment which operates under the constant RF reflection magnitude mode without interference of an external current;

FIG. **37**(*d*) is an image of the area on the surface of the object obtained through the second embodiment which operates under the constant RF reflection magnitude mode with the presence of an external current;

FIG. **37**(*e*) is an image of the area on the surface of the object obtained through the second embodiment which operates under the constant current mode with the presence of an external current; and

FIG. **38** is a circuit diagram illustrating a third embodiment of the RF reflectometry scanning tunneling microscope according to the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Referring to FIG. **8**, a first embodiment of a radio-frequency (RF) scanning tunneling microscope **3** according to the present invention is suitable for observing a surface of an object **20**, and comprises a probe **10** which is adapted to be positioned relative to the surface of the object **20**, and to interact with the object **20** to form a tunneling resistor R_t therebetween. The RF scanning tunneling microscope **3** further comprises an RF resonant circuit **31**, a first directional coupler **32**, an RF signal generator **33** and an RF signal measuring device **4**. The RF resonant circuit **31** includes an inductor L that has a first end **34** connected to the probe **10**, and a second end **35**, a capacitor C_p connected to the first end **34** of the inductor L, and a resistor R_p connected in parallel with the capacitor C_p. The RF resonant circuit **31** is to cooperate with the tunneling resistor R_t to form a LCR resonant circuit in which the inductor L is connected to a parallel connection of the capacitor C_p, the resistor R_p and the tunneling resistor R_t. An equivalent circuit of the LCR resonant circuit is illustrated in FIG. **9**.

A bias voltage may be applied between the probe **10** and the object **20**. For example, the object **20** is applied with a bias voltage V_b and the probe **10** is grounded. When the probe **10** is positioned sufficiently close to the surface of the object **20**, the tunneling effect occurs so as to result in the tunneling resistor R_t therebetween.

In a pre-tuning stage, inductance of the inductor L, capacitance of the capacitor C_p and resistance of the resistor R_p are adjusted in advance such that the LCR resonant circuit resonates at a resonant frequency, which is defined by:

$$\omega_{LC} = \sqrt{\frac{1}{LC}\left(1 - \frac{L}{CR^2}\right)},$$

where ω_{LC} represents an angular frequency associated with the resonant frequency, L represents inductance of the inductor L, C represents capacitance of the capacitor C_p, and R represents resistance of the resistor R_p.

In practice, since resistance of the tunneling resistor R_t is substantially of megaohm to gigaohm scale, and since the resistance of the resistor R_p is substantially of kiloohm scale, resistance of the tunneling resistor R_t is much larger than that of the resistor R_p, i.e., $R_t \gg R_p$. When the resistance of the tunneling resistor R_t is substantially infinite (i.e., the probe **10** is kept away from the object **20**), the resistance $R_{\|}$ of a parallel connection of the resistor R_p and the tunneling resistor R_t (i.e., $R\|=R_t//R_p$) is very close to the resistance of the resistor R_p, i.e., $R \approx R_p$. Therefore, the resonant frequency of the LCR resonant circuit is determined in a condition that the LCR resonant circuit may achieve optimum impedance matching when the probe **10** is kept away from the object **20**, i.e., $R=R_p$. That is to say, impedance of the LCR resonant circuit Z_t corresponds to output impedance Z_o (50 ohms), and a reflection coefficient Γ for the LCR resonant circuit is minimum. When the probe **10** is moved to approach the object **20** so that the resistance of the tunneling resistor R_t decreases to a finite value, the resistance $R_{\|}$ of said parallel connection is substantially equal to but smaller than the resistance of the resistor R_p. The LCR resonant circuit thus fails to achieve impedance matching such that the reflection coefficient Γ changes. In this way, variations of the reflection coefficient Γ are decided by the impedance of the LCR resonant circuit Z_t, i.e.,

$$Z_t = \frac{L}{C \times R}.$$

When the resistance R of said parallel connection is subtly changed, the impedance Z_t is also subtly changed, such that the reflection coefficient Γ is further subtly changed.

A relationship between the reflection coefficient Γ and a division of the resistance of the tunneling resistor R_t by the resistance of the resistor R_p is illustrated in a log-log plot as shown in FIG. **10**, in which the reflection coefficient Γ (i.e., the S-parameter S_{11}) is varied according to variation of the resistance of the tunneling resistor R_t. Within a relatively large range of the resistance of the tunneling resistor R_t compared with that shown in FIG. **7**, the variation of the reflection coefficient Γ with respect to the resistance of the tunneling resistor R_t represents a substantially monotonic and linear configuration. Therefore, the issues of misjudgment of the scanning result and unstable feedback control which usually happen in a conventional RF scanning tunneling microscope resulting from the non-monotonic and nonlinear relationship between the return loss and the resistance of the tunneling resistor may be overcome.

Referring once again to FIG. **8**, the first directional coupler **32** is coupled electrically to the second end **35** of the inductor L of the RF resonant circuit **31**, and has a main path **321** and a coupling path **322**. The RF signal generator **33** is coupled electrically to the first directional coupler **32**, is operable to generate an RF signal, and is adapted to output the RF signal via the main path **321** of the first directional coupler **32** to the LCR resonant circuit. The RF signal is reflected by the LCR resonant circuit so as to result in a reflected RF signal. The reflected RF signal is transmitted via the coupling path **322** of the first directional coupler **32** to the RF signal measuring device **4** which is coupled electrically to the first directional coupler **32**. The RF signal measuring device **4** is adapted to receive from the LCR resonant circuit via the coupling path **322** of the first directional coupler **32** the reflected RF signal, and generates a scanning result associated with the surface of the object **20** based on the reflected RF signal. The RF signal measuring device **4** may also adjust an altitude of the probe **10** with respect to the surface of the object **20** based on the reflected RF signal (i.e., feedback control).

If a return loss of the LCR resonant circuit is desired to be maintained above 20 dB, and if the LCR resonant circuit is desired to operate at a higher frequency (hundreds of megahertz), the inductance of the inductor L or the capacitance of the capacitor C_p should be relatively small (referring to

$$\omega_{LC} = \sqrt{\frac{1}{LC}\left(1 - \frac{L}{CR^2}\right)}$$

as described above). Moreover, the resistance of the resistor R_p should be large enough since the variation of the reflection coefficient Γ depends on a difference between the resistance of the resistor R_p and the resistance $R_{\|}$ of said parallel connection $R_t//R_p$. Therefore, the higher the resistance of the resistor R_p is, the greater will be the variation of the reflection coefficient Γ. However, since the resistance of the resistor R_p is substantially equal to

$$R_p = \frac{L}{C \times Z_o},$$

the resistance of the resistor R_p is hardly set at a higher value. Even if stray capacitance on a printed circuit board (<1.0 pF) is adopted to implement the capacitance of the capacitor C_p, it is still very difficult to set the resistance of the resistor R_p above several kilo ohms.

In order to overcome the aforementioned issue, referring to FIG. **11**, the RF resonant circuit **31** may further include an auxiliary capacitor C_{pi} that is connected to the second end **35** of the inductor L. The RF resonant circuit **31** is to cooperate with the tunneling resistor R_t to form a π-type LCR resonant circuit. Capacitance of the auxiliary capacitor C_{pi} is set at a higher value so that the resistance of the resistor R_p may be set at a higher value. Since the resonant frequency is predominantly decided by the inductance of the inductor L and the capacitance of the capacitor C_p, after the resonant frequency and the resistance of the resistor R_p are set, the capacitance of the auxiliary capacitor C_{pi} may be determined (usually in a range from several picofarads to tens of picofarads). Moreover, since the resistance of the tunneling resistor R_t usually ranges from tens of mega ohms to 1 G ohms, an upper limit of the resistance of the resistor R_p may be set to about 100K ohms, such that the variation of the reflection coefficient Γ with respect to the same resistance of the tunneling resistor R_t may be greater by virtue of addition of the auxiliary capacitor C_{pi}.

A structure of the π-type LCR resonant circuit also offers an opportunity to adjust the resonant frequency of the π-type LCR resonant circuit in real time. Since the resistance of the resistor R_p is fixed, adjustment of the resonant frequency relies on adjustment of the capacitances of the capacitor C_p and the auxiliary capacitor C_{pi}. Referring to FIG. **12**, the RF resonant circuit **31** may further include a first voltage-controlled capacitor VC_p, and a second voltage-controlled capacitor VC_{pi}. The first voltage-controlled capacitor VC_p is connected in series with the capacitor C_p of the RF resonant circuit **31**, and has a capacitance adjusted using a first bias voltage Bias1 to thereby adjust the resonant frequency at which the π-type LCR resonant circuit resonates. The second voltage-controlled capacitor VC_{pi} is connected in series with the auxiliary capacitor C_{pi} of the RF resonant circuit **31**, and has a capacitance adjusted using a second bias voltage Bias2 to thereby adjust an impedance of the π-type LCR resonant circuit. In this way, the π-type LCR resonant circuit may be controlled to select, within a predetermined operating frequency range, a frequency of the RF signal that is to be measured, so as to attempt different types of physical measurements.

The RF signal measuring device **4**, based on the reflected RF signal received from the first directional coupler **32**, is operable to measure the variation of the reflection coefficient Γ (i.e., S**11**) of the π-type LCR resonant circuit with respect to the resistance of the tunneling resistor R_t. Since the first directional coupler **32** is non-ideal and the directivity thereof is finite (in practice, a directivity in a specified used frequency range of 20 to 30 dB or more is chosen), the reflected RF signal received at the RF signal measuring device **4** via the coupling path **322** (coupling loss is considered) is accompanied by a leaked component of the RF signal that is leaked from the main path **321** to the coupling path **322** while the RF signal is transmitted via the main path **321** of the first directional coupler **32** to the π-type LCR resonant circuit so as to result in a to-be-compensated combined signal RFr as best shown in FIG. **13**. Further, when a magnitude of the RF signal transmitted via the main path **321** of the first directional coupler **32** to the π-type LCR resonant circuit is relatively large, a magnitude of the leaked component of the RF signal leaked from the main path **321** to the coupling path **322** may be even larger than a magnitude of the reflected RF signal. Aside from the reflected RF signal, the leaked component of the RF signal which may be regarded as a background signal is also transmitted to the RF signal measuring device **4**, such that the variation of the reflected RF signal which is desired to be measured by the RF signal measuring device **4** is relatively subtle compared to the to-be-compensated signal RFr which is actually measured by the RF signal measuring device **4**. The adverse influence of the leaked component of the RF signal hinders measurement of the variation of the reflected RF signal.

For example, the magnitude of the leaked component of the RF signal (i.e., the background signal) outputted from the first directional coupler **32** typically ranges from −20 dBm to −40 dBm. When atomic and nanoscale features of surface of the object **20** are to be observed, the variation of the reflected RF signal outputted from the π-type LCR resonant circuit may be 0.01 dB or even lower. Although the reflected RF signal may be amplified by an RF power amplifier with low noise and low distortion to have the magnitude of around −10 dBm, the variation of the reflected RF signal is still maintained at the same 0.01 dB. It is difficult for a modern power detector to directly detect a difference between −10.00 dBm and −10.01 dBm, or even smaller differences, since the noise level in the power detector may be approximate to or larger than this 0.01 dB variation.

In order to overcome the aforementioned issue, referring to FIG. **13**, the RF reflectometry scanning tunneling microscope **3** of the present invention further comprises a 2-way power splitter **36** which has two output ports, which is coupled electrically to the RF signal generator **33**, which splits the RF signal generated by the RF signal generator **33** into first and second RF signal parts, and which outputs the first and second RF signal parts to the first directional coupler **32** and the RF signal measuring device **4** via the output ports, respectively. The reflected RF signal received at the RF signal measuring device **4** via the first directional coupler **32** is accompanied by a leaked component of the first RF signal part which is outputted from the 2-way power splitter **36** and which passes through the first directional coupler **32**. The leaked component of the first RF signal part is leaked from the main path **321** to the coupling path **322** of the first directional coupler **32**. The RF signal measuring device **4** further includes an RF signal compensating circuit **41**.

The RF signal compensating circuit **41** includes a first voltage-controlled gain amplifier VGA which is coupled electrically to the coupling path **322** of the first directional coupler **32**, a second voltage-controlled gain amplifier VGAR which is coupled electrically to one of the output ports of the 2-way power splitter **36**, and a phase shifter VPhase which is coupled electrically to the second voltage-controlled gain amplifier VGAR. The first voltage-controlled gain amplifier VGA amplifies the reflected RF signal received from the LCR resonant circuit via the first directional coupler **32** and the leaked component of the first RF signal part to result in a first signal. The second voltage-controlled gain amplifier VGAR amplifies the second RF signal part received from the 2-way power splitter **36** (i.e., a reference signal Ref). The phase shifter VPhase adjusts a phase of the second RF signal part amplified by the second voltage-controlled gain amplifier VGAR to result in a second signal.

When the resistance of the tunneling resistor R_t is relatively large, for example, 10 G ohms or much larger, the RF signal generator **33** is operated to generate the RF signal. Since the π-type LCR resonant circuit has been set to achieve impedance matching in this condition, the magnitude of the reflected RF signal resulting from reflection of the first RF signal part by the π-type LCR resonant circuit is very low. Therefore, the reflected RF signal inputted to the first voltage-controlled gain amplifier VGA via the first directional coupler **32** may be considered fixed, and which in combination with the leaked component of the first RF signal part forms the background signal and may be regarded as being inputted to the first voltage-controlled gain amplifier VGA and being amplified thereby. That is to say, in this condition, the first signal only contains the aforementioned background signal amplified by the first voltage-controlled gain amplifier VGA. Since gain of the second voltage-controlled gain amplifier VGAR and phase of the phase shifter VPhase may be adjusted, the aforementioned background signal amplified by the first voltage-controlled gain amplifier VGA, and the second signal have substantially the same amplitude and are substantially 180 degrees out of phase. The RF signal compensating circuit **41** further includes a combiner **44** which is coupled electrically to the first voltage-controlled gain amplifier VGA and the phase shifter VPhase. The combiner **44** outputs a compensated reflected RF signal by adding the second signal to the first signal so as to cancel out the aforementioned background signal that is amplified by the first voltage-controlled gain amplifier VGA and that is contained in the first signal. In this condition, the compensated reflected RF signal is zero or approximate to zero.

In this way, the leaked component of the first RF signal part leaked from the main path **322** to the coupling path **321** of the first directional coupler **32** may be cancelled out, so that the compensated reflected RF signal outputted from the combiner **44** of the RF signal compensating circuit **41** is able to totally represent the variation of the reflected RF signal resulting from variation of the resistance of the tunneling resistor R_t.

The RF signal measuring device **4** further includes an RF power amplifier **45** coupled electrically to the combiner **44** of the RF signal compensating circuit **41**, an RF power detector **46** coupled electrically to the RF power amplifier **45**, and a computer **70** coupled electrically to the RF power detector **46**. The RF power amplifier **45** amplifies the compensated reflected RF signal outputted by the combiner **44**. The RF power detector **46** detects magnitude of power of the compensated reflected RF signal that is amplified by the RF power amplifier **45**. The computer **70** generates the scanning result associated with the surface of the object **20** based on the magnitude of power of the compensated reflected RF signal detected by the RF power detector **46**.

As shown in FIG. **13**, the first embodiment of the RF reflectometry scanning tunneling microscope **3** according to the present invention further comprises a bias tee circuit **37** which is coupled electrically to the RF resonant circuit **31** and the main path **321** of the first directional coupler **32**, a current-to-voltage converter **39** which is coupled electrically to the bias tee circuit **37**, and a scanning controller **38** which is coupled electrically to the current-to-voltage converter **39**. The bias tee circuit **37** includes a DC-blocking capacitor C_s which is coupled electrically between the RF resonant circuit **31** and the main path **321** of the first directional coupler **32**, and a high frequency choke (RFC) which is coupled electrically between the RF resonant circuit **31** and the current-to-voltage converter **39**. In the present invention, an initial procedure is performed before the object **20** is scanned. In the initial procedure, the probe **10** is to be positioned relative to the object **20** by a sufficient distance, the frequency and amplitude of the RF signal generated by the RF signal generator **33** are set, and the gain of the first voltage-controlled gain amplifier VGA of the RF signal compensating circuit **41** is adjusted, such that the power of the first signal outputted by the first voltage-controlled gain amplifier VGA reaches a custom normalized operating power range (for example, −10 dBm to −30 dBm). The gain of the second voltage-controlled gain amplifier VGAR and the phase of the phase shifter VPhase may be subsequently adjusted, such that the leaked component of the first RF signal part and the reflected RF signal from the RF resonant circuit **31** that are amplified and that are contained in the first signal, and the second signal have substantially the same amplitude and are substantially 180 degrees out of phase. The combiner **44** adds the second signal to the first signal and outputs the compensated reflected RF signal via a 2-way power splitter **49** to a spectrum analyzer **40** which indicates the magnitude of the compensated reflected RF signal. Through observing the degree of weakening of the magnitude of the compensated reflected RF signal, the degree of cancellation of the component of the first RF signal part (i.e., the background signal) may be determined. For example, in a condition that the normalized power of the first signal outputted by the first voltage-controlled gain amplifier VGA is −10 dBm, if the power of the compensated reflected RF signal outputted by the RF signal compensating circuit **41** is −70 dBm, the degree of cancellation of the leaked component of the first RF signal part is 60 dB. Therefore, after the initial procedure has been completed, the power of the compensated reflected RF signal outputted by the RF signal compensating circuit **41** should be approximate to zero. If the initial procedure is required to be fine-tuned, a coarse tuning step is performed by moving the probe **10** toward the surface of the object **20**. The probe **10** is configured to allow a tunneling current I_t to flow between the probe **10** and the object **20** when a bias voltage is applied between the probe **10** and the object **20**. The RF resonant circuit **31** is configured to output the tunneling current I_t via the bias tee circuit **37** to the current-to-voltage converter **39** which amplifies the tunneling current I_t, converts the tunneling current I_t thus amplified into an output voltage, and outputs the output voltage to the scanning controller **38**. The scanning controller **38** controls the probe **10** based on the output voltage so that the altitude of the probe **10** with respect to the surface of the object **20** may be adjusted. After determining according to the output voltage that the tunneling current I_t has reached a predetermined value, the scanning controller **38** controls the probe **10** so as to increase the altitude of the probe **10** with respect to the surface of the object **20**, and the aforementioned initial procedure is performed once again. In this way, variation of capacitance as a result of the probe **10** approaching the surface of the probe **20** may be cancelled out.

In the first embodiment, the first voltage-controlled gain amplifier VGA, the second voltage-controlled gain amplifier VGAR, and the phase shifter VPhase are controlled by the computer **70**, but may be alternatively controlled through manual operation. Referring to FIG. **14**, a circuit diagram of the first voltage-controlled gain amplifier VGA is illustrated. An input signal (i.e., the reflected RF signal accompanied by the leaked component of the first RF signal part) is first amplified by 20 dB though a 20-dB amplifier **140**. The input signal thus amplified is outputted to a digital step attenuator **141** with 1 dB minimum resolution, and is attenuated thereby so as to result in an attenuated signal. The attenuated signal is subsequently outputted to two series connected selective 20-dB amplifiers **142** and **143**, and the magnitude of the attenuated signal is amplified thereby to reach a predetermined value (the range of amplification is from −10 dB to +60 dB), so as to result in the first signal. Referring to FIG. **15**, a circuit diagram of the second voltage-controlled gain amplifier VGAR is illustrated. The gain of the second voltage-controlled gain amplifier VGAR is not necessarily large since the magnitude of the second RF signal part received from the 2-way power splitter **36** (i.e., the reference signal Ref) is originally larger than that of the leaked component of the first RF signal part which is leaked from the main path **322** to the coupling path **321** of the first directional coupler **32** (i.e., the background signal). However, since the magnitude of the second RF signal part received from the 2-way power splitter **36** is required as much as possible to be equal to that of the background signal of the first RF signal part during a compensation operation of the RF signal compensating circuit **41**, relatively good resolution of the second voltage-controlled gain amplifier VGAR is desired. When the resolution of the second voltage-controlled gain amplifier VGAR reaches 0.0001 dB, the 40 dB degree of cancellation of the background signal may be obtained. When the resolution of the second voltage-controlled gain amplifier VGAR reaches 0.000001 dB, the 60 dB degree of cancellation of the leaked component may be obtained. Therefore, aside from a digital step attenuator **151** followed by two series connected selective 20-dB amplifiers **152** and **153** similar to those of the first voltage-controlled gain amplifier VGA, the second voltage-controlled gain amplifier VGAR further includes an analog voltage-controlled attenuator **154**, and two 16-bit digital-to-analog converters **155** and **156** which respectively have voltage conversion ranges of 5 V and 0.1 V, and which generate output voltage signals for controlling the voltage-controlled attenuator **154**, so as to achieve the required resolution.

In addition, for the purpose of precise 180-degree phase shift performed by the phase shifter VPhase, an operation range thereof should exceed 180 degrees, and precision thereof should be better than degree scale. The reason is that if both the magnitude of the background signal of the first RF signal part, and that of the second RF signal part are −10 dBm, a one degree phase difference between the background signal of the first RF signal part, and the second RF signal part will result in a −45 dBm residual signal after the compensation operation of the RF signal compensating circuit **41**, while a 0.1 degree phase difference will result in only a −65 dBm residual signal. Referring to FIG. **16**, in practice, the phase shifter VPhase of the first embodiment performs large angle phase shift by selecting among signal transmission paths with different lengths for adjusting a length of a transmission path of a signal (i.e., the second RF signal part amplified by the second voltage-controlled gain amplifier VGAR). The phase shifter VPhase further includes an attenuator **160** which attenuates the signal (for example, −6 dB), and a voltage-controlled phase shifter **161** which is one of a CLC-type and LC-type phase shifter composed of a voltage-controlled capacitor and an inductor, and which fine tunes a phase of the signal attenuated by the attenuator **160** to result in a shifted signal. The phase shifter VPhase further includes two 16-bit digital-to-analog converters **162** and **163** which respectively have voltage conversion ranges of 5 V and 0.1 V, and which generate output voltage signals for controlling the voltage-controlled phase shifter **161**. In this way, the phase shifter VPhase may achieve at least 0.001 degree resolution. The phase shifter VPhase further includes an impedance-matched amplifier **164** which amplifies the shifted signal outputted by the voltage-controlled phase shifter **161** to result in the second signal.

Since the compensation operation of the RF signal compensating circuit **41** is only effective for signals with a specific frequency, high order harmonic components in the to-be-compensated signal RFr are not cancelled out. Moreover, since the RF power detector **46** is implemented by a power detector which is capable of operating in a wideband, the high order harmonic components in the to-be-compensated signal RFr may be still contained in an output signal of the RF power detector **46**, and a signal-to-noise ratio of the compensated reflected RF signal is reduced. Therefore, as shown in FIG. **13**, the RF signal measuring device **4** further includes a band-pass filter **48** which is coupled electrically to an output terminal of the combiner **44** of the RF signal compensating circuit **41**, and which filters the compensated reflected RF signal outputted by the combiner **44**. Further, if the signal-to-noise ratio is of great concern, the band-pass filter **48** may be implemented using one of a crystal filter and a surface acoustic wave filter which have relatively high Q factors. A narrower bandwidth of the band-pass filter **48** contributes to the increase of the signal-to-noise ratio of the compensated reflected RF signal. However, these kinds of filters available on the market are mostly designed for commercial frequency bands, and are not necessarily suitable for the required frequency and bandwidth of the present invention.

Therefore, referring to FIG. **13**, the RF signal measuring device **4** further includes a mixer **47**, and a local oscillator LO that generates a local oscillator signal. The local oscillator signal has a frequency that corresponds to a sum of or a difference between the frequency of the compensated reflected RF signal and an operating frequency of the band-pass filter **48**. Taking the compensated reflected RF signal having the frequency of 820 MHz for example, when a commercial band-pass filter **48** having the operating frequency of 374 MHz is used, the frequency of the local oscillator signal may be set to 820−374=446 MHz, or 820+374=1194 MHz. Subsequently, the mixer **47** mixes the frequencies of the local oscillator signal and the compensated reflected RF signal outputted by the RF signal compensating circuit **41**, so as to shift the frequency of the compensated reflected RF signal to an operating frequency band of the commercial band-pass filter **48**. The band-pass filter **48** filters the compensated reflected RF signal having the frequency shifted by the mixer **47** to result in a filtered signal. The RF power amplifier **45** amplifies a filtered signal outputted from the band-pass filter **48**, and transmits the filtered signal thus amplified to the RF power detector **46**. In this way, the signal-to-noise ratio of the compensated reflected RF signal may be significantly promoted.

In the first embodiment of the RF reflectometry scanning tunneling microscope **3**, the magnitude of the compensated reflected RF signal is only associated with the tunneling resistor R_t. Referring to FIG. **17**, a relationship among the reflection coefficient Γ, resistance of the tunneling resistor R_t, the tunneling current I_t, and the bias voltage V_b, which is derived from experimental results, is illustrated. It is evident from this relationship that under the different tunneling current I_t and bias voltage V_b, if the resistance of the tunneling resistor R_t is fixed, the reflection coefficient Γ (represented by shades) is also kept constant. Since the tunneling resistor R_t is determined according to electron configurations on the surface of the object **20** and the probe **10**, the variation of the reflection coefficient Γ measured in the first embodiment actually results from the near-field effect (i.e., within a nanometer distance).

In order to prove that the variation of the reflection coefficient Γ corresponds to the tunneling current I_t, in the first embodiment, a surface of graphite is given as an example for the surface of the object. Referring to FIG. **18**, a relationship that is between a variation of the compensated reflected RF signal ΔΓ and the tunneling current I_t and that is obtained by scanning along a line is illustrated. Each rising and falling along the relationship between the variation of the compensated reflected RF signal ΔΓ and the tunneling current I_t represents a signal of a respective carbon atom. It is evident from FIG. **18** that the variations of the compensated reflected RF signal ΔΓ and the tunneling current I_t are highly consistent with each other. When the probe **10** is slightly moved away from the surface of the object **20**, the tunneling current I_t disappears, and the compensated reflected RF signal no longer changes. Therefore, it is the near field effect that leads to the variation of the compensated reflected RF signal ΔΓ.

When a scanning range of the first embodiment expands from a line to a plane, the scanning result associated with the surface of the object **20** may be illustrated in 3D in a RF scanning image as shown in FIG. **19** and a current scanning image as shown in FIG. **20**. It is evident from the RF and current scanning images that they have a high correlation therebetween. Each single atom may be clearly recognized, and a signal-to-noise ratio of the RF scanning image shown in FIG. **19** is even better than that of the current scanning image shown in FIG. **20**. Therefore, since the variations of the compensated reflected RF signal ΔΓ and the tunneling current I_t are highly consistent with each other, the former may be used as a substitute for the latter to serve as a feedback control mechanism such that the probe **10** may be controlled to oscillate up and down along with the surface of the object **20**. Similar to the constant current mode, when the magnitude of the compensated reflected RF signal is constant, i.e., the tunneling resistor R_t is constant, the altitude of the probe **10** with respect to the surface of the object **20** may be also kept fixed (i.e., a constant RF reflection magnitude mode). For example, the first embodiment is configured to operate in the constant current mode and the constant RF reflection magnitude mode, respectively for scanning the same area on the surface of the object **20**, and two images obtained under the respective constant current mode and the constant RF reflection magnitude mode are illustrated in FIG. **21** and FIG. **22**, respectively. It is evident from FIG. **21** and FIG. **22** that through these two modes, very consistent surface images of the object **20** may be obtained. Alternatively, a phase of the reflected RF signal may be kept constant in the constant RF reflection magnitude mode.

Referring to FIG. **23**, in the first embodiment, the probe **10** includes a piezoelectric ceramic crystal (PZT) **52** which is disposed along a Z-axis **51** of the probe **10**, and which is driven to control the altitude of the probe **10** with respect to the surface of the object **20** so as to actuate vibration of the probe **10**. Referring to FIG. **24**, when the altitude of the probe

10 with respect to the surface of the object **20** is increased to an extent that the tunneling current I_t disappears, the magnitude of the compensated reflected RF signal is kept fixed.

In order to compare bandwidths between a DC scanning response (i.e., the tunneling current I_t is used for feedback control) and an RF scanning response (i.e., the compensated reflected RF signal is used for feedback control), the amplitudes of power of each of the tunneling current I_t and the compensated reflected RF signal are measured while gradually increasing the frequency of a driving signal for driving the PZT **52**. It is evident from an experimental result illustrated in FIG. **25** that when the frequency of the driving signal is increased from 100 Hz to 500 MHz, the amplitude of the tunneling current I_t begins to drop at 10 KHz, and a response at 100 KHz is −7 dB (about ⅕). On the other hand, the amplitude of the compensated reflected RF signal remains flat until the frequency of the driving signal reaches 500 MHz (an upper limit for an oscilloscope used for the measurement). This detecting bandwidth is far beyond an operating bandwidth of any existing scanning tunneling microscope.

Furthermore, the scanning controller **38** of the first embodiment is able to generate the driving signal for controlling vibration of the probe **10** based on at least one of the variation of the tunneling current I_t and the variation of the compensated reflected RF signal $\Delta\Gamma$. In practice, different combinations may be adopted for implementing the feedback control. For example, solely the variation of the tunneling current I_t is adopted, solely the variation of the compensated reflected RF signal $\Delta\Gamma$ is adopted, or both are adopted. Since the bandwidth of the RF signal is higher, the variation of the compensated reflected RF signal $\Delta\Gamma$ is more favorable in feedback control. Referring to FIG. **26**, in one configuration of the first embodiment, the scanning controller **38** includes a first signal processor **61**, a second signal processor **62**, an adder, and an amplifier **63**. The first signal processor **61** processes the output voltage which is outputted by the current-to-voltage converter **39** and which may represent the variation of the tunneling current I_t. The second signal processor **62** processes the magnitude of power of the compensated reflected RF signal which is detected by the RF power detector **46** and which may represent the variation of the compensated reflected RF signal $\Delta\Gamma$. The adder outputs a result by adding the output voltage processed by the first signal processor and the magnitude of power of the compensated reflected RF signal processed by the second signal processor **62** in a certain proportion. The amplifier **63** amplifies the result outputted by the adder so as to generate the driving signal for driving the PZT **52** of the probe **10**.

Referring to FIG. **27**, in another configuration of the first embodiment, the scanning controller **38** includes a first signal processor **61**, an amplifier **63**, and a second signal processor **64**. The first signal processor **61** processes the output voltage outputted by the current-to-voltage converter **39** to result in a processed output voltage. The amplifier **63** amplifies the processed output voltage from the first signal processor **61**, and outputs the processed output voltage thus amplified to a first end of PZT **52**. The second signal processor **64** processes the magnitude of power of the compensated reflected RF signal detected by the RF power detector **46**, and outputs the magnitude of power of the compensated reflected RF signal thus processed to a second end of the PZT **52** for driving the PZT **52** of the probe **10**. In this way, the compensated reflected RF signal may be free from the limitation of the amplifier **63**.

It is noted that, referring to FIG. **28**, when the tunneling effect occurs between the probe **10** and the object **20**, aside from the tunneling resistor R_t formed between the probe **10** and the object **20**, a tunneling barrier capacitor C_t is also formed between the probe **10** and the object **20** in practice. For the formation of the tunneling resistor R_t, the probe **10** must be sufficiently close to the object **20**. In the first embodiment, a bias voltage V_b may be applied to the object **20**. The probe **10** is grounded and is adapted to cooperate with the object **20** to form the tunneling resistor R_t therebetween as a result of the tunneling effect. The tunneling current I_t is outputted from the RF resonant circuit **31**, via the high frequency choke RFC of the bias tee circuit **37**, to the current-to-voltage converter **39**. If the object **20** is a material with high electrical conductivity, the tunneling resistor R_t is a major factor that affects the magnitude of the reflected RF signal. At this moment, the capacitance of the tunneling barrier capacitor C_t is generally below attofarad scale (10^{-18} farad), and barely affects the π-type LCR resonant circuit. The aforementioned embodiment is configured to perform scanning upon the object **20** under this condition.

On the contrary, when the object **20** is a dielectric material with high electrical resistivity, even if the probe **10** is very close to the surface of the object **20**, the resistance of the tunneling resistor R_t formed between the probe **10** and the object **20** is still very large, such that the tunneling resistor R_t barely affects the magnitude of the reflected RF signal. At this moment, capacitance of the tunneling barrier capacitor C_t varies according to variation of the altitude of the probe **10** with respect to the surface of the object **20**. Therefore, referring to FIG. **13**, the RF signal compensating circuit **41** of the first embodiment further includes a second directional coupler **42** that has a coupling path **421** and that is disposed between the phase shifter VPhase and an input terminal of the combiner **44** of the RF signal compensating circuit **41**. The RF signal measuring device **4** further includes a third directional coupler **43** that has a coupling path **431** and that is disposed at an output terminal of the combiner **44**, an amplifier **71** that is coupled electrically to the coupling path **431** of the third directional coupler **43**, and a phase difference detector **72** that is coupled electrically to an output terminal of the amplifier **71** and the coupling path **421** of the second directional coupler **42**. The second directional coupler **42** couples the second signal outputted by the phase shifter VPhase to the phase difference detector **72**. The third directional coupler **43** couples the compensated reflected RF signal outputted by the combiner **44** to the amplifier **71**. The amplifier **71** amplifies the compensated reflected RF signal received from the third directional coupler **43** to result in a third signal, and outputs the third signal to the phase difference detector **72**. The phase difference detector **72** detects a phase difference between the second signal and the third signal. The phase difference detected by the phase difference detector **72** may reflect the reactive effect of tunneling energy barrier, i.e., the dielectric property of the object **20**. The computer **70** may also obtain the scanning result of the surface of the object **20** based on variation of the phase difference detected by the phase difference detector **72**. Therefore, the first embodiment may also measure the reactive effect on the surface of the object **20** by detecting the variation of the phase difference so as to achieve higher temporal and spatial resolutions.

Moreover, referring to FIG. **29**, another configuration for providing a bias voltage V_b between the probe **10** and the object **20** is illustrated. The object **20** is grounded. The current-to-voltage converter **39** is configured to provide a bias voltage V_b via the high frequency choke RFC of the bias tee circuit **37** to the RF resonant circuit **31**, such that the π-type LCR resonant circuit is applied with the bias voltage V_b. In this configuration, since the magnitude of the tunneling current I_t flowing though the tunneling resistor R_t is desired to be measured, for preventing the tunneling current I_t from flowing through the resistor R_p instead of the tunneling resistor R_t (because $R_p << R_t$), the RF resonant circuit **31** further includes a blocking capacitor C_b connected in series with the resistor R_p so as to block the DC current flowing through the resistor R_p. Further, when capacitance of the blocking capacitor C_b is relatively large (greater than tens of nanofarad scale), the blocking capacitor C_b is substantially equivalent to a short circuit for the RF signal having the operating frequency of hundreds of megahertz, but is substantially equivalent to an open circuit for a direct current. In this way, the tunneling current I_t may entirely flow through the tunneling resistor R_t.

Referring to FIG. **30**, a second embodiment of the RF reflectometry scanning tunneling microscope **3** (referred to as RFSTM **3** hereinafter) according to the present invention differs from the first embodiment in that the RFSTM **3** further comprises a shielding casing **5**. The shielding casing **5** is configured to house the probe **10** and the RF resonant circuit **31** therein, and is formed with an opening configured for extension of a tip **100** of the probe **10** therethrough and outwardly of the shielding casing **5** (see FIG. **31**), so as to protect the RF resonant circuit **31** from interference of an external current that is generated by an external electron/current field with a relatively low frequency. The electron/current field may be incident electrons emitted by an electron gun, secondary electrons, Auger electrons, photoelectrons excited by radiation, a faradaic current generated as a result of electrochemical reaction, or combinations thereof. Preferably, referring to FIG. **32**, the shielding casing **5** is further configured to house the bias tee circuit **37** and the current-to-voltage converter **39**, such that the probe **10**, the RF resonant circuit **31**, the bias tee circuit **37**, and the current-to-voltage converter **39** may be provided with good protection against interference.

Aside from the constant RF reflection magnitude mode (referred to as constant RF mode hereinafter), the second embodiment of the RFSTM **3** also operates in the constant current mode in which a conventional tunneling microscope usually operates. When the probe **10** and the object **20** are exposed to an environment under the influence of the external electron/current field, for example, a faradaic current field generated in a liquid-phase electrochemical reaction tank as best shown in FIG. **33**, the external current (not shown) generated by the external electron/current field may be combined with the tunneling current I_t to serve as an aggregated current I. The aggregated current I is then amplified by the current-to-voltage converter **39**, thereby adversely influencing the feedback control mechanism of the present invention, so that the scanning result of the surface of the object **20** may not be obtained properly.

On the other hand, if the second embodiment of the RFSTM **3** operates in the constant RF mode, owing to the shielding effect provided by the shielding casing **5**, the compensated reflected RF signal is not affected by the interference of the external electron/current field. Referring to FIG. **34**, it is evident that even though the aggregated current I increases from 40 nano-amps to 80 nano-amps as a result of the presence of the external current, the amplitude of the compensated reflected RF signal remains steady. The altitude of the probe **10** with respect to the surface of the object **20** thus remains unchanged. In this way, by utilizing the compensated reflected RF signal for feedback control of the altitude of the probe **10** with respect to the surface of the object **20**, the RFSTM **3** of the present invention may be effectively relieved from interference of the external current.

Specifically, for the second embodiment of the RFSTM **3** which operates respectively in the constant current mode and the constant RF mode for feedback control, a relationship between the external current and the altitude of the probe **10** with respect to the surface of the object **20** is further explained in the following paragraphs. For the sake of brevity, the altitude of the probe **10** with respect to the surface of the object **20** is referred to as an altitude Z of the probe **10** in the following paragraphs.

Referring to FIG. **35**(*a*) and FIG. **35**(*b*), the external current generated by the external electron/current field is modulated into a square-wave, such that the waveform of the aggregated current I is changed as best shown in these figures. FIG. **35**(*a*) clearly indicates that, under the constant RF mode for feedback control, the altitude Z of the probe **10** is subtly changed as a result of thermal shift, and is not significantly correlated to the aggregated current I. On the other hand, referring to FIG. **35**(*b*), under the constant current mode for feedback control, the altitude Z of the probe **10** is significantly proportional to the integral of the aggregated current I in the form of a square-wave. Therefore, it is evident that the altitude Z of the probe **10** is more vulnerable to the external current under the constant current mode for feedback control compared with the altitude Z of the probe **10** is to the external current in the constant RF mode for feedback control.

Furthermore, the external current generated by the external electron/current field may be replaced by a photoelectric current which is excited by an X-ray excitation source for observation of a relationship between the aggregated current I and the altitude Z of the probe **10** under the constant RF mode for feedback control. At the instant when the X-ray excitation source is activated, the aggregated current I rises instantaneously to form a step-wise waveform, as best shown in FIG. **36**(*a*), while the compensated reflected RF signal and the altitude Z of the probe **10** do not change according to the variation of the aggregated current I. On the other hand, when the X-ray excitation source is switched alternately between an ON state and an OFF state, as best shown in FIG. **36**(*b*), the variation of the aggregated current I significantly corresponds to switching of the X-ray excitation source, but the compensated reflected RF signal and the altitude Z of the probe **10** do not change correspondingly. That is to say, for the RFSTM **3** which operates under the constant RF mode for feedback control, the compensated reflected RF signal and the altitude Z of the probe **10** may not change according to the external current.

In order to verify the efficiency of the second embodiment of the RFSTM **3**, it is evident from FIG. **37**(*a*) and FIG. **37**(*b*) that an image of an area on the surface of the object **20** (a sheet of gold on mica) obtained under the constant current mode without interference of an external current is similar to an image of the area on the surface of the object **20** obtained under the constant RF mode with the presence of the external current.

Further, in the following test, the RFSTM **3** is operating under the constant RF mode, and the probe **10** and the object **20** are exposed to both a testing environment without an external current and a testing environment with the presence of a modulated (12 Hz) external current. It is evident that an image of an area on the surface of the object **20** obtained without interference of the external current (see FIG. **37**(*c*)) is similar to that of the object **20** obtained with the presence of the external current (see FIG. **37**(*d*)).

Moreover, the RFSTM **3** is configured to operate under the constant current mode for obtaining an image of the area on the surface of the object **20**. Referring to FIG. **37**(*e*), when one-third of the area on the surface of the object **20** has been scanned, an external current is provided. It may be noted that the image of the area on the surface of the object **20** is severely influenced after provision of the external current. In other words, as long as the second embodiment of the RFSTM **3** is operating under the constant RF mode, the scanning result associated with the surface of the object **20** may be obtained successfully regardless of interference of the external current.

As a result, in expectation of presence of an external current, the RFSTM **3** of the present invention is set to operate under the constant RF mode, and the magnitude of power of the compensated reflected RF signal detected under the constant RF mode may be directly utilized to move the probe **10** toward the surface of the object **20** to an extent that the tunneling effect occurs, such that a clear image of the area on the surface of the object **20** may be thus obtained even with the presence of the external current. However, in expectation of absence of an external current, the RFSTM **3** may be first set to operate under the constant current mode, and moves the probe **10** toward the surface of the object **20** to an extent that the tunneling effect occurs. Subsequently, the RFSTM **3** may be switched to operate under the constant RF mode, so that control of the altitude Z of the probe **10** may be alleviated from the influence of the external current, and a clear scanning result of the surface of the object **20** may be thus obtained.

Referring to FIG. **38**, a third embodiment of the RFSTM **3** according to the present invention differs from the second embodiment in that the mixer **47** is omitted and two mixers together with two band-pass filters are added, and the oscillator signal generated by the local oscillator LO is provided to the added mixers, respectively.

Specifically, the RF signal measuring device **4** of the third embodiment of the present invention, aside from the elements mentioned in the first embodiment, further includes a first input mixer **50** together with a first input band-pass filter **471** which are coupled between the 2-way power splitter **36** and the RF signal compensating circuit **41**, and a second input mixer **51** together with a second input band-pass filter **472** which are coupled between the first directional coupler **32** and the RF signal compensating circuit **41**.

The first input mixer **50** receives the reference signal Ref from the 2-way power splitter **36** and the oscillator signal from the local oscillator LO, and mixes frequencies of the reference signal Ref and the oscillator signal so as to generate a first mixed signal. The first mixed signal includes an operating frequency sub-signal and a non-operating frequency sub-signal. The second input mixer **51** receives the to-be-compensated signal RFr from the first directional coupler **32** and the oscillator signal from the local oscillator LO, and mixes frequencies of the to-be-compensated signal RFr and the oscillator signal so as to generate a second mixed signal. The second mixed signal includes an operating frequency sub-signal and a non-operating frequency sub-signal.

The first input band-pass filter **471** receives the first mixed signal from the first input mixer **50**, filters out the non-operating frequency sub-signal of the first mixed signal, and outputs the first mixed signal, which has the non-operating frequency sub-signal filtered out, to the RF signal compensating circuit **41**. The second input band-pass filter **472** receives the second mixed signal from the second input mixer **50**, filters out the non-operating frequency sub-signal of the second mixed signal, and outputs the second mixed signal, which has the non-operating frequency sub-signal filtered out, to the RF signal compensating circuit **41**.

The RF signal compensating circuit **41** receives the first mixed signal and the second mixed signal, and subjects the first mixed signal and the second mixed signal to the compensation operation mentioned in the first embodiment so as to output the compensated reflected RF signal. The RF power amplifier **45** is coupled electrically to the RF signal compensating circuit **41** for receiving the compensated reflected RF signal, and amplifies the compensated reflected RF signal to result in an amplified compensated signal. The band-pass filter **48** is coupled electrically to the RF power amplifier **45** for receiving the amplified compensated signal, and filters the amplified compensated signal to result in a filtered compensated signal. The 2-way power splitter **49** is coupled electrically to the band-pass filter **48** via the third directional coupler **43** for receiving the filtered compensated signal, and splits the filtered compensated signal into a first split signal and a second split signal. The RF power detector **46** is coupled electrically to the 2-way power splitter **49** for detecting a magnitude of power of the first split signal. The scanning controller **38** is coupled electrically to the RF power detector **46** for receiving the magnitude of power of the first split signal detected by the RF power detector **46**, and controls the probe **10** based on the magnitude of power of the first split signal. The computer **70** is coupled electrically to the RF power detector **46**, and generates the scanning result associated with the surface of the object **20** based on the magnitude of power of the first split signal detected by the RF power detector **46**.

The third directional coupler **43** is coupled electrically between the band-pass filter **48** and the 2-way power splitter **49**, and has the coupling path **431**. The amplifier **71** is coupled electrically to the coupling path **431** of the third directional coupler **43**. The third directional coupler **43** couples the filtered compensated signal outputted by the band-pass filter **48** to the amplifier **71**. The amplifier **71** amplifies the filtered compensated signal received from the third directional coupler **43** to result in an amplified coupled signal, and outputs the amplified coupled signal to the phase difference detector **72**. The phase difference detector **72** is coupled electrically to an output terminal of the amplifier **71** and the coupling path **421** of the second directional coupler **42**. The phase difference detector **72** detects a phase difference between a phase-shifted signal that is associated with the first mixed signal and that is outputted by the second directional coupler **42**, and the amplified coupled signal outputted by the amplifier **71**. Specifically, the phase-shifted signal is similar to the second signal mentioned in the first embodiment which is obtained by subjecting the first mixed signal to the second voltage-controlled gain amplifier VGAR and the phase shifter VPhase.

The computer **70** is further coupled electrically to the phase difference detector **72**, and may also obtain the scanning result of the surface of the object **20** based on variation of the phase difference detected by the phase difference detector **72**.

In the third embodiment of the present invention, the first input mixer **50** together with the first input band-pass filter **471**, and the second input mixer **51** together with the second input band-pass filter **472** are arranged respectively at input terminals of the RF signal compensating circuit **41** for the reason that the reference signal Ref and the to-be-compensated signal RFr may have frequencies down-converted and filtered, such that the operating frequency sub-signal of the first mixed signal and the operating frequency sub-signal of the second mixed signal thus obtained may have frequencies optimized. In this way, the RF signal compensating circuit **41** is alleviated from processing the non-operating frequency sub-signal of the first mixed signal and the non-operating frequency sub-signal of the second mixed signal, and performs the aforementioned compensation operation merely upon the operating frequency sub-signal of the first mixed signal and the operating frequency sub-signal of the second mixed signal so as to output the compensated reflected RF signal. The compensated reflected RF signal is then provided to the RF power amplifier **45** for subsequent processing mentioned above. Therefore, a signal-to-noise ratio of the scanning result obtained in the third embodiment may be further promoted.

To sum up, the RFSTM **3** of the present invention has the following advantages:

1. The present invention is capable of measuring the effect of the tunneling resistor R_t formed between the probe **10** and the object **20** by means of the reflected RF signal. Furthermore, the phase difference between the second signal and the third signal may be detected so as to reflect the reactive effect on the surface of the object **20**.

2. By means of the shielding effect provided by the shielding casing **5**, the RFSTM **3** which operates under the constant RF mode may be alleviated from influence of the external current resulting from the external electron/current field, and the scanning result of the surface of the object **20** thus obtained is as clear as that obtained under the constant current mode without interference of the external electron/current field.

3. By respectively arranging the first input mixer **50** together with the first input band-pass filter **471**, and the second input mixer **51** together with the second input band-pass filter **472** at input terminals of the RF signal compensating circuit **41**, the signal-to-noise ratio of the scanning result thus obtained may be further promoted.

While the present invention has been described in connection with what are considered the most practical embodiments, it is understood that this invention is not limited to the disclosed embodiments but is intended to cover various arrangements included within the spirit and scope of the broadest interpretation so as to encompass all such modifications and equivalent arrangements.

What is claimed is:

1. A radio-frequency (RF) reflectometry scanning tunneling microscope suitable for observing a surface of an object, said RF reflectometry scanning tunneling microscope comprising:

a probe adapted to be positioned relative to the surface of the object, and to interact with the object to form a tunneling resistor therebetween;

an RF resonant circuit including

an inductor that has a first end connected to said probe,

a capacitor connected to the first end of said inductor, and

a resistor connected in parallel with said capacitor,

wherein said RF resonant circuit is to cooperate with the tunneling resistor to form a LCR resonant circuit in which said inductor is connected to a parallel connection of said capacitor, said resistor and the tunneling resistor;

a first directional coupler coupled electrically to a second end of said inductor of said RF resonant circuit, and configured to receive an RF signal, to output the RF signal thus received to the LCR resonant circuit, and to receive a reflected RF signal that results from reflection of the RF signal by the LCR resonant circuit; and

an RF signal measuring device adapted to receive the reflected RF signal from the LCR resonant circuit via said first directional coupler, and operable to generate a scanning result associated with the surface of the object based on the reflected RF signal; and

wherein said RF signal measuring device includes

a local oscillator which generates a local oscillator signal,

a first input mixer which receives a reference signal associated with the RF signal and the oscillator signal from said local oscillator, and which mixes frequencies of the reference signal and the oscillator signal so as to generate a first mixed signal, and

a second input mixer which receives the reflected RF signal from said first directional coupler and the oscillator signal from said local oscillator, and which mixes frequencies of the reflected RF signal and the oscillator signal so as to generate a second mixed signal.

2. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, wherein said RF resonant circuit further includes an auxiliary capacitor that is connected to the second end of said inductor, said RF resonant circuit to cooperate with the tunneling resistor to form a Π-type LCR resonant circuit.

3. The RF reflectometry scanning tunneling microscope as claimed in claim **2**, wherein said RF resonant circuit further includes:

a first voltage-controlled capacitor which is connected in series with said capacitor of said RF resonant circuit, and which has a capacitance adjusted using a first bias voltage to thereby adjust a resonant frequency at which the Π-type LCR resonant circuit resonates; and

a second voltage-controlled capacitor which is connected in series with said auxiliary capacitor of said RF resonant circuit, and which has a capacitance adjusted using a second bias voltage to thereby adjust an impedance of the Π-type LCR resonant circuit.

4. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, further comprising:

an RF signal generator which is operable to generate the RF signal; and

a 2-way power splitter which has two output ports, which is coupled electrically to said RF signal generator, which splits the RF signal generated by said RF signal generator into two RF signal parts, and which outputs the RF signal parts to said first directional coupler and said RF signal measuring device via said output ports, respectively;

wherein the reflected RF signal received at said RF signal measuring device via said first directional coupler is accompanied by a leaked component of the RF signal part which is outputted from said 2-way power splitter and which passes through said first directional coupler;

wherein said RF signal measuring device further includes an RF signal compensating circuit which amplifies the reflected RF signal received from the LCR resonant circuit via said first directional coupler and the leaked component of the RF signal part to result in a first signal, and which amplifies and adjusts a phase of the RF signal part received from said 2-way power splitter to result in a second signal; and

wherein the leaked component of the RF signal part that is amplified and that is contained in the first signal, and the second signal have substantially the same amplitude and are substantially 180 degrees out of phase, said RF signal compensating circuit outputting a compensated reflected RF signal by adding the second signal to the first signal so as to cancel out the leaked component of the RF signal part that is amplified and contained in the first signal.

5. The RF reflectometry scanning tunneling microscope as claimed in claim **4**, wherein said RF signal compensating circuit includes:

a first voltage-controlled gain amplifier which amplifies the reflected RF signal received from the LCR resonant circuit via said first directional coupler and the leaked component of the RF signal part to result in the first signal;

a second voltage-controlled gain amplifier which amplifies the RF signal part received from said 2-way power splitter;

a phase shifter which adjusts the phase of the RF signal part amplified by said second voltage-controlled gain amplifier to result in the second signal, the leaked component of the RF signal part that is amplified and contained in the first signal, and the second signal being substantially 180 degrees out of phase; and

a combiner which adds the second signal to the first signal and which outputs the compensated reflected RF signal.

6. The RF reflectometry scanning tunneling microscope as claimed in claim **5**,

wherein said RF signal compensating circuit further includes a second directional coupler that has a coupling path and that is disposed between said phase shifter and an input terminal of said combiner of said RF signal compensating circuit;

wherein said RF signal measuring device further includes

a third directional coupler that has a coupling path and that is disposed at an output terminal of said combiner,

an amplifier that is coupled electrically to the coupling path of said third directional coupler, and

a phase difference detector that is coupled electrically to an output terminal of said amplifier and the coupling path of said second directional coupler; and

wherein said second directional coupler couples the second signal to said phase difference detector, said third directional coupler coupling the compensated reflected RF signal outputted by said combiner to said amplifier, said amplifier amplifying the compensated reflected RF signal received from said third directional coupler to result in the third signal, and outputting the third signal to said phase difference detector, said phase difference detector detecting a phase difference between the second signal and the third signal.

7. The RF reflectometry scanning tunneling microscope as claimed in claim **4**, wherein said RF signal measuring device further includes:

an RF power detector which detects magnitude of power of the compensated reflected RF signal outputted by said RF signal compensating circuit;

a scanning controller which controls said probe based on the magnitude of power of the compensated reflected RF signal detected by said RF power detector; and

a computer which generates the scanning result associated with the surface of the object based on the magnitude of power of the compensated reflected RF signal detected by said RF power detector.

8. The RF reflectometry scanning tunneling microscope as claimed in claim **7**, further comprising:

a bias tee circuit coupled electrically to said RF resonant circuit and said first directional coupler; and

a current-to-voltage converter coupled electrically to said bias tee circuit;

wherein said probe is configured to allow a tunneling current to flow between said probe and the object when a bias voltage is applied between said probe and the object;

wherein the RF signal part passing through said first directional coupler is outputted to the LCR resonant circuit via said bias tee circuit, the reflected RF signal resulting from the LCR resonant circuit is outputted therefrom to said first directional coupler via said bias tee circuit, said RF resonant circuit being configured to output the tunneling current via said bias tee circuit to said current-to-voltage converter which amplifies the tunneling current, converts the tunneling current thus amplified into an output voltage, and outputs the output voltage to said scanning controller, said scanning controller controlling said probe further based on the output voltage.

9. The RF reflectometry scanning tunneling microscope as claimed in claim **8**,

wherein said probe includes a piezoelectric ceramic crystal which is driven to actuate vibration of said probe; and

wherein said scanning controller includes

a first signal processor which processes the output voltage outputted by said current-to-voltage converter,

a second signal processor which processes the magnitude of power of the compensated reflected RF signal detected by said RF power detector,

an adder which outputs a result by adding the output voltage processed by said first signal processor and the magnitude of power of the compensated reflected RF signal processed by said second signal processor, and

an amplifier which amplifies the result outputted by said adder so as to generate a driving signal for driving said piezoelectric ceramic crystal of said probe.

10. The RF reflectometry scanning tunneling microscope as claimed in claim **8**,

wherein said probe includes a piezoelectric ceramic crystal which is driven to actuate vibration of said probe; and

wherein said scanning controller includes

a first signal processor which processes the output voltage outputted by said current-to-voltage converter to result in a processed output voltage,

an amplifier which amplifies the processed output voltage from said first signal processor, and outputs the processed output voltage thus amplified to a first end of said piezoelectric ceramic crystal, and

a second signal processor which processes the magnitude of power of the compensated reflected RF signal detected by said RF power detector, and outputs the magnitude of power of the compensated reflected RF signal thus processed to a second end of said piezoelectric ceramic crystal for driving said piezoelectric ceramic crystal of said probe.

11. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, a bias voltage being applied to the object, wherein said probe is grounded and is adapted to cooperate with the object to form the tunneling resistor therebetween as a result of the tunneling effect when said probe is disposed sufficiently close to the object.

12. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, the object being grounded, said RF reflectometry scanning tunneling microscope further comprising a high frequency choke coupled electrically to said RF resonant circuit, the LCR resonant circuit being applied with a bias voltage via said high frequency choke, said probe being configured to allow a tunneling current to flow between said probe and the object;

wherein said RF resonant circuit further includes a blocking capacitor connected in series with said resistor for preventing the tunneling current from flowing through said resistor.

13. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, further comprising:

a shielding casing configured to house said probe and said RF resonant circuit therein, so as to prevent the reflected RF signal from interference of an external electron/current field.

14. The RF reflectometry scanning tunneling microscope as claimed in claim **13**, wherein said shielding casing is formed with an opening configured for extension of a tip of said probe therethrough and outwardly of said shielding casing.

15. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, wherein said RF reflectometry scanning tunneling microscope is configured to operate in a constant RF reflection magnitude mode during which said RF signal measuring device utilizes the reflected RF signal for feedback control of said probe, a magnitude of power or a phase of the reflected RF signal being kept constant in the constant RF reflection magnitude mode.

16. The RF reflectometry scanning tunneling microscope as claimed in claim **1**, wherein said RF signal measuring device further includes:

a first input band-pass filter which is coupled electrically to said first input mixer for receiving the first mixed signal therefrom, and which filters out a non-operating frequency sub-signal of the first mixed signal; and

a second input band-pass filter which is coupled electrically to said second input mixer for receiving the second mixed signal therefrom, and which filters out a non-operating frequency sub-signal of the second mixed signal.

17. The RF reflectometry scanning tunneling microscope as claimed in claim **16**, wherein said RF signal measuring device further includes:

an RF signal compensating circuit which is coupled electrically and respectively to said first input band-pass filter and said second input band-pass filter for receiving the first mixed signal and the second mixed signal, and which subjects the first mixed signal and the second mixed signal to a compensation operation so as to output a compensated reflected RF signal;

an RF power amplifier which is coupled electrically to said RF signal compensating circuit for receiving the compensated reflected RF signal, and which amplifies the compensated reflected RF signal to result in an amplified compensated signal;

a band-pass filter which is coupled electrically to said RF power amplifier for receiving the amplified compensated signal, and which filters the amplified compensated signal to result in a filtered compensated signal;

a 2-way power splitter which is coupled electrically to said band-pass filter for receiving the filtered compensated signal, and which splits the filtered compensated signal into a first split signal and a second split signal;

an RF power detector which is coupled electrically to said 2-way power splitter for detecting a magnitude of power of the first split signal;

a scanning controller which is coupled electrically to said RF power detector for receiving the magnitude of power of the first split signal detected thereby, and which controls said probe based on the magnitude of power of the first split signal; and

a computer which is coupled electrically to said RF power detector, and which generates the scanning result associated with the surface of the object based on the magnitude of power of the first split signal.

18. The RF reflectometry scanning tunneling microscope as claimed in claim **17**, wherein said RF signal measuring device further includes:

a third directional coupler which is coupled electrically between said band-pass filter and said 2-way power splitter;

an amplifier which is coupled electrically to said third directional coupler that couples the filtered compensated signal outputted by said band-pass filter to said amplifier, said amplifier amplifying the filtered compensated signal received from said third directional coupler to result in an amplified coupled signal; and

a phase difference detector which is coupled electrically to an output terminal of said amplifier and said RF signal compensating circuit, said phase difference detector detecting a phase difference between a phase-shifted signal that is associated with the first mixed signal and that is outputted by said RF signal compensating circuit, and the amplified coupled signal outputted by said amplifier.

19. The RF reflectometry scanning tunneling microscope as claimed in claim **18**, wherein said computer further obtains the scanning result of the surface of the object based on variation of the phase difference detected by said phase difference detector.

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