Study on the Measurement of Microscopic RF Field Distribution with a MFM Tip Exploiting a Beat Signal Between a CPW and an Exciting Coil

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Abstract—This paper describes a measurement of microscopic radio frequency (RF) field distribution with a magnetic force microscope (MFM) tip exploring a beat signal from a coplanar waveguide (CPW). This CPW has a 5 μm wide signal line and a 50 μm wide ground line assuming a basic model of power/ground lines in radio frequency integrated circuit (RFIC) chips. To produce a beating field near the CPW, a signal current with a fixed frequency in the GHz range is supplied to the CPW and a reference current with a slightly different frequency from a signal frequency is supplied to the coil arranged above the cantilever, and then an attempt is made to detect the beating field between the CPW and the coil using a MFM tip.

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I. INTRODUCTION

Smaller, lighter cellular phones with multiple functions are in practical use with rapid development of RF circuit integration technology. However, as the line pitch becomes smaller, the so-called micro-electromagnetic compatibility (EMC) is becoming an urgent issue. To address the challenge, microscopic measurements and analysis of electromagnetic field propagation and radiation occurring in radio frequency integrated circuits (RFIC) are essential.

Until recently, the detection of RF fields distribution from RFIC has been made using shielded loop coils [1],[2], magneto-optic probes [3],[4] and scanning superconducting quantum interference device (SQUID) microscope [5], etc. Unfortunately, a trade-off between spatial resolution and detection sensitivity is unavoidable for these conventional methods. A magnetic resonance force microscope (MRFM) provides both high spatial resolution and sensitivity, but it has been used only for fundamental research [6]-[8], because the operating frequency is determined by material parameters of a coating film on the tip. On the other hand, a magnetic force microscopy (MFM) has been developed to clarify static magnetic field distribution near the surface of ferromagnetic materials. If a MFM tip can detect RF fields from RFIC which are much weaker than the field from ferromagnetic materials, it would be a great advance for microscopic development of EMC technology.

Until now, we have been studying two types of high-frequency MFM (HF-MFM) in an attempt to measure RF magnetic near-fields in RFIC chips with submicron resolution: One is that the RF magnetic field to be measured is amplitude-modulated (AM) [9]-[11]. It was successfully demonstrated that the RF magnetic near-field on the CPW with a carrier frequency up to 1.0 GHz, which is higher than the cantilever resonance frequency, was measured using a Ni-Fe coated tip [10]. This method is useful for analytical study of field distribution near a signal line if the signal can be amplitude-modulated.

The other is that a detection of beating between two RF fields where one is the magnetic field to be measured and the other is intentionally produced with a reference frequency. The reference frequency is adjusted so that the beat excites the mechanical cantilever resonance. It is speculated that this method is very effective for the direct measurement of field distribution near signal lines, ground lines and power lines in RFIC chips. However, it was not fully verified whether a tip with a mechanical resonance of a few tens of kHz is able to detect the beat between the signal and the reference frequencies in MHz and GHz ranges.

Herein the validity of this method is verified using a CPW which is a basic model of power/ground lines in RFIC chips and an exciting coil. The signal current with a GHz-range frequency is supplied to the CPW, the reference current with a slightly different frequency from the signal frequency is supplied to the coil arranged above the cantilever, and then an attempt is made to detect the beating field between the CPW and the coil using a MFM tip.
II. EXPERIMENTAL PROCEDURE

A. Measurement method

The beating field strength was evaluated by the oscillation amplitude at the cantilever resonance frequency at room temperature in air. Figure 1 shows the experiment setup. The beating field was produced by a signal current supplied to the CPW through a power divider and a ground-signal-ground (GSG) pin type probe and a reference current supplied to a semicircular exciting coil with a diameter of 100 μm. The coil was placed at the fixed height of approximately 30 μm above the cantilever [Figs. 1(b),(c)]. The signal current was fixed in a GHz-range frequency. The reference was adjusted to scan the beat frequency. To separate the RF magnetic signal from electric field noises, an attenuator, a phase shifter and a bypass capacitor were equipped in the setup [Dotted line area in Fig. 1(a)]. Because the cantilever acted as both a magnet and a plate-type condenser [12], these circuit elements cancelled the electric potentials of the MFM tip and CPW, reducing the electric force interaction between the tip and the electric near-field near the CPW.

B. Fabrication of CPW

A CPW was fabricated by electron-beam lithography, dc magnetron sputtering, and a lift-off technique onto a glass substrate with a relative permittivity of 7.0. The CPW was composed of a 300-nm-thick Cu layer sandwiched between two 5-nm-thick Cr layers, Cr (5 nm)/Cu (300 nm)/Cr (5 nm)/glass. The widths of the signal line, gap, and ground line of the fabricated CPW were 5.0, 6.0, and 50.0 μm, respectively, which resulted in a characteristic impedance of approximately 191.0 Ω up to 2.0 GHz [Fig. 2]. The length of the CPW was 9.0 mm.

Fig. 2. Variation in the characteristics impedance $Z_0$ of the CPW (signal line width 5 μm, ground line width 50 μm) with frequency.

C. MFM tip

The MFM tip was a Si cantilever coated with a 50-nm-thick Ni-Fe film, which was initially magnetized in the perpendicular direction. The spring constant of the cantilever, quality factor of the tip, and tip apex radius were approximately 1.4 N/m, 100–150, and 40–50 nm, respectively.

III. THEORETICAL PREDICTION

In case of RF magnetic near-field on the CPW, the vertical component of beating field between the CPW and the coil is given by

$$H_{beat} = H_{cpw} \cos \theta \cos 2\pi f_{cpw} + H_{coil} \cos \theta \cos 2\pi f_{coil}, \quad (1)$$

where $H_{cpw}$ and $H_{coil}$ are the magnetic field from the CPW and that from the coil, $\theta$ and $\phi$ are the angle of $H_{cpw}$ and that of $H_{coil}$ from vertical axis in the cross-section of the CPW. $f_{cpw}$ and $f_{coil}$ are the signal current frequency and the coil current one.

The force exerted on the MFM tip by the RF magnetic near-field on the CPW, $F_M$, is represented by

$$F_M = m \frac{dH_{beat}}{dz} + \left\{ H_{cpw} \frac{dH_{cpw}}{dz} \cos 2\theta \cos 2\pi f_{cpw} + H_{coil} \frac{dH_{coil}}{dz} \cos 2\phi \cos 2\pi f_{coil} \right\} \times \cos (2\pi f_{coil} \delta), \quad (2)$$

where $m$, $z$, $f_{cpw}$, $f_{coil}$ and $\delta$ are the magnetization of the MFM tip, the lift height from the CPW surface, the cantilever resonance frequency, the component of beating field between the CPW and the coil is given by $H_{beat} = H_{cpw} \cos \theta \cos 2\pi f_{cpw} + H_{coil} \cos \theta \cos 2\pi f_{coil}$, respectively.

When the MFM tip approached the CPW surface, the beating field drove the tip with maximum amplitude at the cantilever resonance frequency. The change of oscillation amplitude with scanned beat frequency was detected by a position sensitive detector (PSD) and the signal was analyzed by a lock-in amplifier. All curves of oscillation amplitude vs frequency were measured with a narrow band-width of 80 Hz. It should be noted the cantilever was driven solely by the proximal electromagnetic fields and no other physical forces were applied.
frequency, the average of \( f_{cpw} \) and \( f_{coil} \), and the phase, respectively.

On the other hand, in case of electric near-field on the CPW, the vertical component of beating field between the CPW and the coil is given by

\[
E_{\text{beat}} = E_{cpw} \cos \theta_{cpw} \cos 2\pi f_{cpw} + E_{coil} \cos \theta_{coil} \cos 2\pi f_{coil},
\]

where \( E_{cpw} \) and \( E_{coil} \) are the electric field from the CPW and that from the coil, \( \theta_{cpw} \) and \( \theta_{coil} \) are the angle of \( E_{cpw} \) and that of \( E_{coil} \) from horizontal axis in the cross-section of the CPW. \( f_{cpw} \) and \( f_{coil} \) are the signal current frequency and the coil current one.

The force exerted on the MFM tip by the RF electric near field on the CPW, \( F_t \), is expressed by

\[
F_t = \frac{1}{2} \varepsilon V_{cpw}^2 (V_{ip} - V_{ip})^2
= \frac{1}{2} \left[ \varepsilon V_{cpw}^2 \cos \theta_{cpw} + \varepsilon V_{coil}^2 \cos \theta_{coil} \right]
+ 2 \varepsilon E_{ip} V_{ref} \cos \theta_{ip} \cos \theta_{ref} \cos 2\pi f_{ref} \cos 2\pi f_{ip} \cos (2\pi f_{ip} - \delta),
\]

where \( \varepsilon, V_{cpw}, \) and \( V_{ip} \) are the relative permittivity, potential of the CPW and potential of the cantilever, respectively [13]. These equations indicate that the MFM tip detects both RF magnetic and electric near fields in every signal frequency range using beating field. From this theoretical prediction, these circuit elements cancelled the electric potentials of the MFM tip and CPW, reducing the electric force interaction between the tip and the electric near-field near the CPW, as already described in II.A.

IV. RESULTS AND DISCUSSION

The oscillation amplitude \( A \) was measured at 0.4 \( \mu \)m above the CPW surface on the center-line of gap between the signal line and the ground line. Figure 3 shows the oscillation amplitude \( A \) as a function of the beat frequency for the signal frequency of 1.0 GHz. The amplitude fluctuated but it was clearly seen that the maximum amplitude is at the cantilever resonance frequency of approximately 27.7 kHz, giving evidence that a beating field between an RF field from the CPW and that from the coil is detectable by a MFM tip. The cause of this fluctuation was not identified explicitly, but seems to be temporal phase shift of the beating field. Analysis and modification of the measuring system to remove the fluctuation are in progress.

Figure 4 shows the oscillation amplitude \( A \) at the cantilever resonance frequency as a function of current amplitude for the signal frequency of 1.7 GHz. In case of a fixed signal current amplitude of 9.1 mA [Fig. 4(a)], the oscillation amplitude \( A \) increased linearly as the AC current supplied to the coil increased. This tendency almost agrees with the variation in the oscillation amplitude with the signal current amplitude, as can be noticed in Fig. 4(b). Therefore, it is verified that the mechanical resonance reflects the RF current amplitude.

Moreover, the oscillation amplitude \( A \) was measured at various lift heights \( h \) above the CPW surface on the center-line of the gap between the signal and ground line with a signal frequency of 1.6 GHz. Figure 5 plots the results as a function of \( h \). The oscillation amplitude \( A \) was observed at heights above 0.1 \( \mu \)m, but disappeared below a height of 0.1 \( \mu \)m, suggesting that the tip is absorbed onto the substrate surface. The amplitude markedly decreased with the height up to 0.4 \( \mu \)m, and then monotonically decreased above 0.5 \( \mu \)m. This oscillation amplitude behavior is similar to that for the AC current (or without an amplitude modulation) case, but rate...
that the amplitude decreases with the height $h$ is about twice as large as that for the AC case [9]. This observation may be explained by the point dipole approximation [14],[15]; the cantilever is driven by the gradient of the RF magnetic near-field on the CPW.

In our present work, the RF magnetic near-field near CPW was successfully measured with a signal frequency of 1.0−1.7 GHz. These results demonstrate that a tip with a mechanical resonance of a few tens of kHz has sufficient sensitivity to detect a beat between the signal and reference currents in the GHz-range frequency. It is suggested that GHz-range magnetic near-fields in the RFIC chip composed of the LSI circuits with submicron fine signal and ground lines may be detected directly with a very high resolution by adopting our proposed measurement, and that this measurement has high potential as the microscopic measurement of EMC technology.

V. CONCLUSIONS

The measurement of microscopic RF field distribution with a Ni-Fe coated MFM tip exploiting a beat signal between the CPW and the coil has been verified. The oscillation amplitude of the MFM tip excited by the beat was measured above the CPW surface for the signal frequency in the GHz range, causing the RF field from the CPW. On the basis of these results, it should be stressed that the technique proposed in this paper has high potential as a new method to measure GHz-range magnetic field distribution in microscale RFIC chips with very high resolution. It is also speculated that this technique is a great advance for microscopic development of EMC technology.

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