Terahertz nanoscopy of spontaneous surface waves on dielectrics

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Abstract

At finite temperature, all matters radiate electromagnetic waves due to their molecular motion, lattice vibration, and bio-protein motion, whose spectra lie mainly in terahertz (THz) region (wavelength $\lambda : 10\sim50$ μm). Probing such spontaneous THz emissions without any external illumination has a potential to reveal local dynamics of objects. To achieve such local phenomena, conventional active microscopes are not well suited since weak radiation from local dynamics can be easily spoiled by much stronger external illumination. We should thus passively detect this weak spontaneous radiation with nanoscale spatial resolution without any external illumination. For such detection, we have recently developed a sensitive scattering-type scanning near-field optical microscope (s-SNOM) with a highly sensitive THz detector, charge sensitive infrared phototransistor (CSIP), $\lambda : 10\sim20$ μm. In this passive s-SNOM, a sharp tungsten probe serves as a scatterer for the surface waves on a room-temperature object. With the s-SNOM, we have achieved spontaneous near-field signals with 20 nm spatial resolution, which has never obtained by any other passive microscope. Theoretical and experimental analyses strongly suggest that passive near-field signals on metals should originate from charge thermal fluctuations of conduction electrons, which is highly confined to sample surface. We have thoroughly studied thermal evanescent waves only on metals with the microscope so far. Much more interesting targets to be studied should be dielectric materials since they show surface phonon resonances in infrared/terahertz region. In this report, we demonstrate the detection of spontaneous surface waves on several dielectric samples (GaAs, SiC, AlN, GaN) and discuss the guiding principle of passive near-field detection. We have achieved different and unique signals on these dielectrics derived from surface phonon and have found that the signal characteristics can be interpreted with the interaction between the probe apex and the surface phonon.

Keywords: Terahertz wave, Passive microscopy, Near-field microscopy, Evanescent wave, Thermal fluctuation

1. Introduction

In general optical microscopy, an external light source illuminates an object and then the optical response (reflection, transmission, etc.) is detected. This active microscopy is presently very useful for appearance check and structural analysis. On the other hand, all materials emit photons due to their local phenomena such as molecular motion, lattice vibration, and bio-protein motion. These spectra from room-temperature objects lie mainly in terahertz (THz) region (wavelength $\lambda : 10\sim50$ μm) [1]. Although probing such spontaneous THz emissions has been strongly required to reveal local dynamics, technical issues have been prevented the realization. However we have recently developed a “passive” scattering-type scanning near-field optical microscope (s-SNOM) in THz region, which probes spontaneous surface waves without any external illumination [2]. Figure 1(a) is a schematic diagram of our passive s-SNOM. The s-SNOM is a home-made system consisting of a confocal THz microscope [3] and a sharp tungsten probe placed at the focal point of the microscope. A sharp tungsten probe (radius of curvature $R = \sim20$ nm) serves as a scatterer for the surface waves on the studied sample placed at room temperature. The scattered evanescent electromagnetic waves are collected by a germanium (Ge) objective lens (numerical aperture, N.A. = 0.60) placed upward in the vertical direction, and re-focused on a helium-cooled ultra-highly sensitive detector called the charge-sensitive infrared phototransistor (CSIP, wavelength range of $\lambda = 14.5 \pm 0.7$ μm) [4]. Figure 1(b) represents the top view photograph of a CSIP detector. With the passive near-field microscope at $\lambda = 14.5$ μm, we have achieved passive near-field signals like Fig. 1(c). Now the spatial resolution reaches 20 nm which has never been achieved by any other passive microscope [5]. Theoretical and experimental analyses have revealed that the passive near-field signals on metals/dielectrics should originate from thermal charge/current fluctuations. We have thoroughly studied thermal evanescent waves only on metals with the microscope so far. Much more interesting targets to be studied should be dielectric materials since they show surface phonon resonances in THz region. In this report, we show thermal near-field signals on several dielectric samples and discuss the guiding principle of passive near-field detection.

2. Passive near-field signals on dielectrics

We studied GaAs, SiC, AlN, and GaN single crystal samples fabricated via electron beam lithography as well as Au for...
reference. Respective wavelengths of the surface phonon resonances are 34.5 μm, 10.6 μm, 11.8 μm, and 14.2 μm. In this experiment, the wavelength of the CSIP detector is 14.5 μm, very close to the GaN resonance. Figure 2 shows the tip height dependence of passive near-field signals over GaAs, SiC, AlN, GaN, and Au. At probe height \( h = 10 \) nm, GaAs, SiC, and AlN showed finite passive near-field signals due to thermally excited phonons. However, surprisingly, we could not find any signal on GaN surface though its phonon-resonance wavelength lies very close to the detection wavelength. In Fig. 2, when the tip (probe) height \( h \) is less than 20 nm, signal amplitudes lie \( \text{AlN} > \text{Au} > \text{SiC} > \text{GaAs} > \text{GaN} \). Figure 3 plots numerical calculations of the amplitude of electromagnetic local density of states (LDOS) at \( h = 10 \) nm. The amplitudes of thermal evanescent waves on metal/dielectric samples are strongly correlated to electromagnetic LDOS [6]. Judging from this calculation, the amplitude order at \( h = 10 \) nm in Fig. 2 is reasonable except GaN. In Fig. 2, GaN shows very unique height dependence. When the tip height is around 10 nm, the signal amplitude is almost zero. On the other hand, as the tip height increases, the signal amplitude also increases. Then when the height is more than 50 nm, the amplitude gradually decreases. Here we try to interpret the result with effective polarizability.

The guiding principle of passive near-field detection can be interpreted with the interaction between the tip and the thermal evanescent waves. In passive near-field microscopy, first the dipoles at the tip apex are generated by spontaneous surface waves. The dipoles at the tip apex then generate mirror dipoles in the studied sample. After that, such optical interactions radiate (scatter) photons and finally the CSIP detects the scattered photons. The effective polarizability of the tip apex plays main roles as well as LDOS. Figure 4 shows the computed values of the effective polarizabilities for each studied material. Here we approximate a tip apex by a spheroid. In Fig. 4, the polarizabilities of AlN, SiC, and GaAs decrease rapidly with increasing probe height, whereas GaN shows very unique height dependence. In the range of 10 – 60 nm, the polarizability of GaN gradually increases, with increasing probe height. Then, over 60 nm, the polarizability gradually decreases. These calculations are relatively similar to experimental results in Fig. 2. Here it should be noted that the surface phonon resonance has very long coherence length (~\( \lambda \)), which means the decay length is very long. In our study, we vertically modulate the tip at \( \Delta h = 100 \) nm at 10 Hz to avoid thermal far-field noises (Planck radiation). Therefore, when probing surface phonon resonances, we obtain very small signals at \( h = 10 \) nm because of the long decay. In Fig. 2 and 4, we find maximum values at \( h = 60 \) nm over GaN. We assume that the interference of surface phonon resonance between the tip and the surface can cause such interesting characteristics. For further understanding the characteristics and the guiding principle, we study dielectrics with other detection wavelengths, which will be shown in the presentation.

**Figure 2.** Tip height dependence of passive near-field signals on dielectrics at \( \lambda = 14.5 \) μm.

**Figure 3.** Calculated LDOS of dielectrics at \( h = 10 \) nm.

**Figure 4.** Effective polarizabilities of tip over dielectrics and Au.

3. Discussion

The guiding principle of passive near-field detection can be interpreted with the interaction between the tip and the thermal evanescent waves. In passive near-field microscopy, first the dipoles at the tip apex are generated by spontaneous surface waves. The dipoles at the tip apex then generate mirror dipoles in the studied sample. After that, such optical interactions radiate (scatter) photons and finally the CSIP detects the scattered photons. The effective polarizability of the tip apex plays main roles as well as LDOS. Figure 4 shows the computed values of the effective polarizabilities for each studied material. Here we approximate a tip apex by a spheroid. In Fig. 4, the polarizabilities of AlN, SiC, and GaAs decrease rapidly with increasing probe height, whereas GaN shows very unique height dependence. In the range of 10 – 60 nm, the polarizability of GaN gradually increases, with increasing probe height. Then, over 60 nm, the polarizability gradually decreases. These calculations are relatively similar to experimental results in Fig. 2. Here it should be noted that the surface phonon resonance has very long coherence length (~\( \lambda \)), which means the decay length is very long. In our study, we vertically modulate the tip at \( \Delta h = 100 \) nm at 10 Hz to avoid thermal far-field noises (Planck radiation). Therefore, when probing surface phonon resonances, we obtain very small signals at \( h = 10 \) nm because of the long decay. In Fig. 2 and 4, we find maximum values at \( h = 60 \) nm over GaN. We assume that the interference of surface phonon resonance between the tip and the surface can cause such interesting characteristics. For further understanding the characteristics and the guiding principle, we study dielectrics with other detection wavelengths, which will be shown in the presentation.

5. Summary

We studied spontaneous surface waves on dielectrics (GaAs, SiC, AlN, GaN). GaAs, SiC, and AlN show finite and reasonable signals, whereas GaN represents unique characteristics. It can be interpreted with the interaction between the tip and the phonon resonances. For further discussions, we will obtain passive near-field signals with other wavelengths.

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References