Development of cryogenic scattering-type thermal near-field microscope

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Due to the lack of a nano-thermal imaging technique at low temperatures, we have developed a cryogenic scattering-type scanning near-field optical microscope (s-SNOM). The system mainly contains a highly sensitive long-wavelength infrared confocal optics and an AFM based on a piezoelectric tuning fork probe. By using the cryogenic s-SNOM, we have successfully detected the surface electromagnetic evanescent fields on a biased NiCr wire. The near-field signals originate from the thermally excited fluctuating charge of conduction electron. In the near future, we expect the s-SNOM enable to investigate kinetics energy of charge/phonon in non-equilibrium nano-devices.

I. INTRODUCTION

THERMAL scattering-type scanning near-field optical microscopy (s-SNOM) is used to probe fluctuating electromagnetic (EM) evanescent fields induced by fluctuating charge/current below the sample surface placed at room temperature in the long-wavelength infrared (LWIR) regime [1,2]. The thermal s-SNOM is equipped with a highly sensitive GaAs/AlGaAs quantum well-based LWIR detector, called charge-sensitive infrared phototransistor (CSIP) [3]. Specific detectivity D^* of the CSIP is ~ 1×10^{16} cm $Hz^{1/2}/W$. Because of the high sensitivity, the thermally excited electromagnetic (EM) evanescent fields can be detected by the thermal s-SNOMs without using any external light source. The spatial resolution of the passive s-SNOM depends on the tip radius and our s-SNOM has achieved ~20 nm [4]. With this non-invasive detection technique, the thermal s-SNOMs have studied nanoscale temperature mapping of lattice temperature in graphene devices [5], metallic wires [6], and energy dissipation of hot-electron in GaAs/AlGaAs quantum well-based devices [7]. Up to now, the thermal s-SNOMs, however, are only able to study the samples in the room-temperature environment.

For expanding the application of the thermal THz s-SNOM to low-temperature (LT) studies such as phase transition materials and energy dissipation in electrotransport devices, we developed an LWIR optical microscope containing a high vacuum chamber, providing 4.2 K environment for both LWIR confocal optical system and atomic force microscope (AFM) system, as shown in Fig. 1 (a). To scatter the EM evanescent fields, an AFM probe is held close to the sample surface. The scattered near fields (NFs) are converted to propagating fields. The propagating fields, containing NF components and background far-field (FF) radiations, are collected by the LWIR confocal microscope and detected by a CSIP (λ = 10.2 ± 0.9 μm). Finally, the NF signal is extracted from the background FF radiation with a demodulation method. Here we report on the development of cryogenic s-SNOM and the measurement of thermally excited evanescent fields on a Joule-heated NiCr wire.

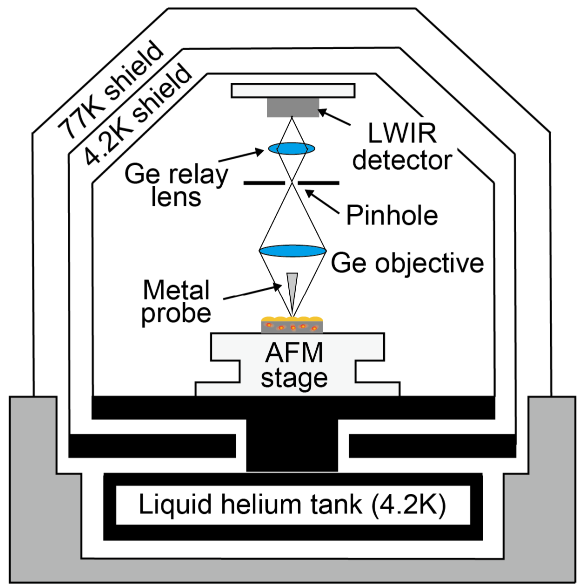

Fig. 1. (a) Schematic diagram of the cryogenic passive s-SNOM equipped with confocal LWIR optics.

II. DEVELOPMENT

The cryogenic LWIR s-SNOM contains a highly sensitive LWIR confocal optical microscope and AFM system based on a quartz tuning fork. To efficiently extract the NF components submerged within a large background FF component emitted from the focal area of the objective, we introduced a confocal optical system to exclude the radiation out of the focal area on the sample surface. In the confocal optics, we use germanium (Ge) meniscus lens design for objective and relay lens to reduce spherical aberration. The Ge meniscus objective has a numerical aperture of 0.35 and a working distance of 12 mm. A pinhole of 60 μm diameter, used to block out stray lights, is mounted between the objective and the relay lens. The LWIR FF radiation emitted by the sample and scattered by the probe tip are collected and focused on the pinhole by the Ge meniscus objective, and then refocused on the photosensitive area (75 × 75 μm^2) of the CSIP by relay lens. The position of the focal point of the objective can be adjusted on the sample surface by vertically moving the confocal optics with a stepping-motor driven mechanical stage.

The AFM system is designed as a quartz tuning fork shear-force feedback system [8]. A sharp tungsten probe is glued to an arm of the tuning fork (Abracon, AB38T). The mechanical resonance frequency of the tuning fork is ~31.8 kHz with a quality factor of 4000 at 5 K. We move the probe tip to the center of the focal point of the Ge meniscus objective by operating stepping-motor driven mechanical xy-stages. For the initial coarse adjustment of the sample toward the probe tip, we use a stepping-motor driven mechanical z-stage. To precisely

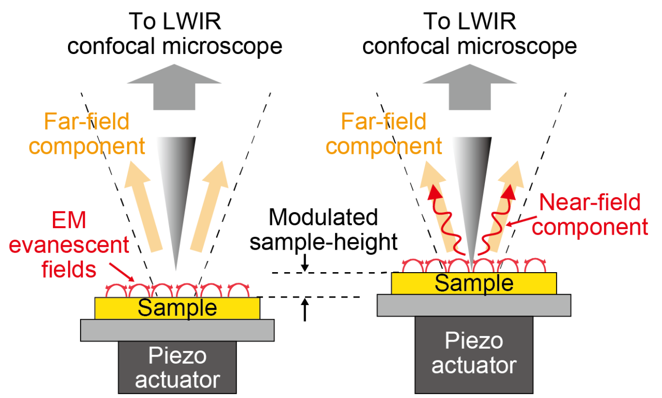

Fig. 2. EM evanescent fields are scattered by the probe tip when the sample surface close to the probe tip. The sample-height modulation technique is applied to extract the NF components out of background far-field components. The sample vibrated vertically with a piezo actuator.

control the tip-sample distance in nanoscale, we use a piezoelectric tube actuator for the sample piezo z-stage. For the purpose of extracting NF signals out of large background radiations, emitting from the material in the focal point, we use a sample-height modulation technique, as shown in Fig. 2. Namely, the tip-sample distance is vibrated with the piezoelectric tube actuator. We modulate the sample-height at a frequency of 9 Hz and amplitude of 100 nm and keep the minimum tip-sample distance at 10 nm. The scattered NF components are collected with the confocal optics and demodulated with a lock-in amplifier at the fundamental frequency of 9 Hz. To obtain an NF image, the sample is scanned by controlling a xy-stepping-motor-driven mechanical stage.

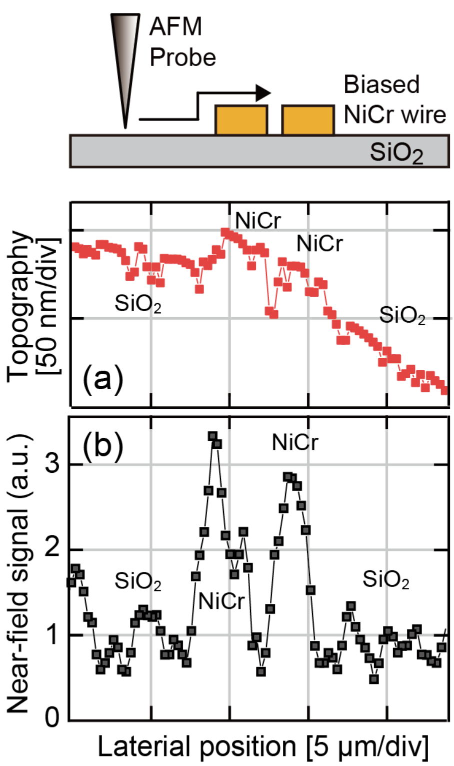

Fig. 3. (a) Topography of NiCr wires with a thickness of 30 nm and a width of 3 μm. (b) Intensity profile of NF signal. The NF detection of thermally excited evanescent field is demonstrated on biased NiCr wire.

III. Results and Discussion

In this work, we prepared an on-chip NiCr filament (30 nm thickness and 3 μm width) as a heater to heat up a Au/NiCr/SiO_2 sample (~175 mW). To check the focal spot size of the confocal optics, we measured the LWIR FF thermal signals at the boundary between Au and SiO_2. They are clearly distinguished due to the difference in emissivity. The spatial resolution of the FF signals is estimated to be ~70 μm.

Based on the FF thermal image and topographic profile, the probe tip can be placed at the center of the focal area to efficiently collect the scattered NFs, as illustrated in Fig. 2. Figures 3 (a) and (b) show a topography and NF signal taken simultaneously on the NiCr/SiO_2 sample at 300 nm step. The SNR of the NF signal on Joule-heated NiCr was about 3 with a 10 s integration time when the bias current was 3.37 mA. According to the fluctuation-dissipation theorem, the NF signals observed on the NiCr surface is ascribed to the EM evanescent fields induced by the thermal stochastic motion of conduction electron [9]. The smaller NF signal on SiO_2 is due to the surface phonon polariton ($\lambda^{SPhP} \approx 8.6$ μm) is far away from the detection wavelength ($\lambda = 10.2 \pm 0.9$ μm) [10].

IV. Summary

A cryogenic LWIR scattering-type s-SNOM with a confocal optical system and quartz tuning folk-based AFM has been developed. We successfully measure the thermally excited NF signals strongly show up on the Joule-heated NiCr narrow wire. In the near future, we expect the cryogenic scattering-type thermal near-field microscope to a variety of study directions, such as local energy dissipation of non-equilibrium charge or phonon in nano-devices and LT transport properties in exotic samples.

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