An improved far-infrared microscope with quantum Hall detectors

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Abstract

A highly-sensitive scanning far-infrared (FIR) microscope is developed. The microscope consists of a silicon solid immersion lens that probes FIR and a condenser lens that focuses the FIR onto a small and highly-sensitive quantum Hall detector. The solid immersion lens is in contact with a sample, which is moved with a mechanical stage. The microscope is successfully applied to image extremely weak cyclotron emission from quantum Hall devices with a spatial resolution about 50μm and a signal-to-noise ratio improved by a factor 18 compared to a previous system.

Key words: quantum Hall effect; cyclotron emission; cyclotron resonance; far-infrared radiation

A number of different local probe techniques has led to developments of a variety of scanning microscopes. An extremely simple scanning far-infrared (FIR) microscope with a resolution better than the FIR wavelength has been recently reported [1,2]. The optical system (Fig. 1 (a)) consists of a single hyper-hemisphere solid immersion lens (SIL) made of silicon (refractive index $n_{\rm Si} = 3.38$), the focal poit of which is designed to be on a two-dimensional electron gas (2DEG) layer in a GaAs/AlGaAs heterostructure crystal: In the quantum Hall effect (QHE) regime at high magnetic fields and a low temperature, the cyclotron radiation emitted from nonequilibrium electrons in the 2DEG layer at a focal point is colimated and guided through a 29-cm-long metal light pipe to a sensitive QHE detector [3]. Unfortunately the system had two deficits. One is a small numerical aperture (NA=1.39), which was needed to avoid significant spherical aberration of the SIL. The other is the lack of addtional lens condensing FIR radiation on the detector. Both these two led to a sensitivity lower than an optimum level.

Here, we develop a higher-performance FIR microscope by introducing a condenser lens (Fig. 1 (b)), which focuses FIR radiation detected by the SIL on a smaller detector. Thanks to the condenser lens, made of polyolefine (TPX) with the refractive index of $n_{\rm TPX} = 1.475$, the silicon SIL can be designed to be aplanatic with the radius of curveture $r_{\rm Si} = 1.40$ mm and the thickness $t = 1.21$ mm, where the refractive index and the thickness of the GaAs substrate are $n_{\rm GaAs} = 3.31$ and $t_{\rm GaAs} = 0.60$ mm. It leads to a larger numerical apature (NA = 2.39) of the SIL, which makes us to expect an increase in the total radiation power reaching the detector by a factor of five compared to the earlier system (Fig. 1(a)). In addition, since the electrical

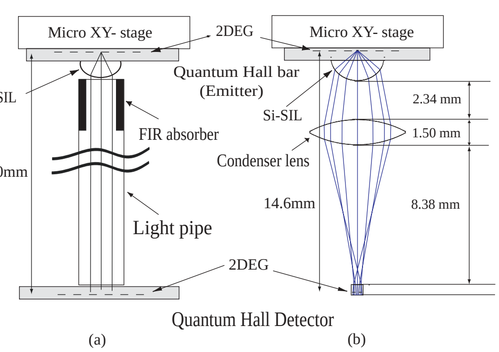

Fig. 1. Schematic of scanning FIR microscopes. A Hall bar sample mounted on a micro XY stage is moved with respect to the SIL. (a) The previous system (Ref. [2]) consisting of a single SIL. (b) The present system with a condensor lens, in which a smaller detector is used.

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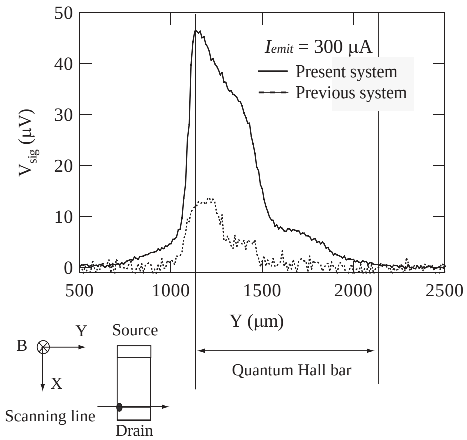

Fig. 2. Comparison of V_{sig} between the previous system and the present system. The time constant is fixed in the lock-in measurements. The lower schematic represents the line along which the probed point is scanned.

noise of detectors reduces in general with reducing the detector size as $\sqrt{A}$, where A is the area of the detector, it is expected that the signal-to-noise (S/N) ratio eventually increases by a factor more than five: If additional loss of radiation is ignored and perfect optical alignment is assumed, the increament by a factor roughly about 100 is expected.

The detector has a tunable and high-sensitive property due to cyclotron resonance in the quantum Hall effect (QHE) regime at low temperatures and under high magnetic fields in 2DEG systems [3]. The detector with a 2DEG channel of a total length $L_{SD} = 6.9$ mm and a width $W_{SD} = 0.02$ mm meandering in an area of $A_{SD} = 0.4 \times 0.4\ \mathrm{mm}^2$ is fabricated on a GaAs/AlGaAs heterostructure crystal with $\mu = 48\ \mathrm{m}^2/\mathrm{Vs}$ and $n_s = 3.4 \times 10^{15}\ \mathrm{m}^2$. As a reference experiment, FIR radiation is studied also in the single SIL system (Fig. 1 (a)) by using a larger detector ($L_{LD} = 168$ mm and $W_{LD} = 0.05$ mm in an area of $A_{LD} = 3.1 \times 3.8\ \mathrm{mm}^2$), fabricated on the same GaAs/AlGaAs crystal. The emitter is a rectangular Hall bar ($1 \times 3\ \mathrm{mm}^2$) fabricated on a different GaAs/AlGaAs heterostructure crystal with the electron mobility $\mu = 38\ \mathrm{m}^2/\mathrm{Vs}$ and the density $n_s = 3.2 \times 10^{15}\ \mathrm{m}^2$.

Figure 2 shows the detector signals, V_{sig}, obtained when the sample is scanned along the width-wise direction of of the Hall bar as illustrated in the lower part of Fig. 2. Here, the Hall bar sample is in the QHE state of the filling factor $\nu = 2$ at the current $I_{emit} = 300\mu$ A at 4.2 K and 7.71 T. It is evident that the S/N ratio is significantly improved in the present system (solid line) compared to the single SIL system (doted line). The amplitude of the detector signal, V_{sig}^{SD}, increases by a factor 3.3 while the noise voltage, V_{noise}^{SD}, is reduced by a factor 5.6, yielding the improvement of the S/N ratio by a factor of 18. Discrepancy from the estimated ideal improvement factor about 100 might be ascribed to an ambiguity of refractive indexes of Si, GaAs, and TPX at low temperatures (4.2 K) and in the THz regions as well as to the loss on the condenser lens and slight misalignment of the optical system. Despite all of these the improvement is significant, demonstrating distinct advantage of the present optical system. Spatial resolution is derived from the experimental results to be about 50 μ m, which is better than the one achieved by the single SIL system. The resolution here is supposed to be determined by the whole optical system rather than by the value of NA of the SIL alone.

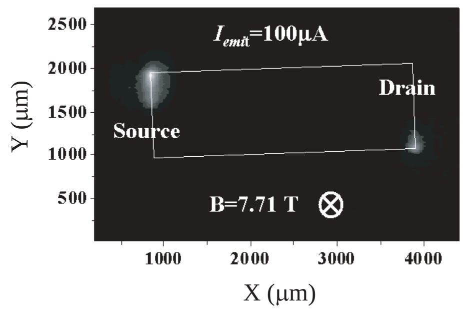

Fig. 3. Image of cyclotron emissions from the QHE Hall bar of $\nu = 2$ at $I_{emit} = 100\mu$ A. The white regions at the corners near terminals indicate significant distribution of cyclotron emission. The white rectangle marks the Hall bar sample.

Figure 3 displays a high-resolution image of the cyclotron emission due to non-equilibrium electrons generated in the QHE Hall bar, obtained by scanning the whole area of the Hall bar. Bright two regions at the diagonally opposite corners near terminals indicate the significant generation of non-equilibrium electrons at these corners, demonstrating the usefulness of this optical scheme for studying detailed distributions of non-equilibrium electrons in quantum Hall devices.

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References

[1] Y. Kawano, Y. Hisanaga, S. Komiyama, Phys. Rev. B 59 (1999) 12537.

[2] Y. Kawano, S. Komiyama, Proc. 25th Int. Conf. Phys. Semicond., Osaka 2000, p.921.

[3] Y. Kawano, Y. Hisanaga, H. Takenouchi, S. Komiyama, J. Appl. Phys. 89 (2001) 4037.