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Far-infrared photoresponse of the magnetoresistance of the two-dimensional electron systems in the integer quantized Hall regime

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We have investigated the far-infrared (FIR) photoinduced resistance change of the two-dimensional electron systems in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunctions in the integer quantized Hall regime. Sensitive photoinduced resistance change ΔR_{xx} is observed only in the vicinity of the quantum Hall states. It is found that the magnitude and polarity of ΔR_{xx} strongly depend on the Landau-level filling factor and the bias current. We have shown that not only a bolometric effect (i.e., electron heating) but also an electronic process due to edge channel transport is responsible for the observed behavior of ΔR_{xx}. The observed photoresponse can be used for realizing very sensitive, narrow-band FIR detectors.

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It was found almost 20 years ago that the diagonal magnetoresistance R_{xx} of the two-dimensional electron systems (2DES's) in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunctions resonantly changes when the samples are irradiated with far-infrared (FIR) radiation under high magnetic fields, B.[1] From the observed systematic relationship between the photon energy and the resonance magnetic field, it was concluded that the resistance change ΔR_{xx} is induced by cyclotron resonance (CR). After this report, several research groups investigated this phenomenon.[2–5] They found that there are not only a resonant component but also a nonresonant component in ΔR_{xx}.[2–4] Furthermore, it was also found that the B dependence of ΔR_{xx} is similar to that of the temperature derivative of R_{xx}.[3] From these facts, it has been understood that ΔR_{xx} is caused by electron/lattice heating due to FIR absorption.

More recently, it has been recognized that nonequilibrium edge channel transport plays important roles in determining transport properties of high-mobility 2DES's under high-magnetic fields; electrons travel over a macroscopic distance in dissipationless edge channels before they are scattered into bulk states.[6–11] However, the effects of edge channel transport on ΔR_{xx} are not clear at present.

In this paper, we have systematically investigated the photoinduced change of the diagonal magnetoresistance ΔR_{xx} of the 2DES's in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunctions in the integer quantized Hall regime and discussed the mechanisms that induce ΔR_{xx}. It is found that ΔR_{xx} appears only in the vicinity of the quantum Hall states (QHS's) and that its magnitude and polarity strongly depend on the bias current I and the Landau-level filling factor $\nu(\equiv hN_s/eB)$. We have shown that not only an electron heating effect, but also an electronic process due to edge channel transport, is responsible for the observed behavior of ΔR_{xx}. Furthermore, we will demonstrate that the observed photoresponse can be used for realizing very sensitive, narrow-band FIR detectors.

The sample used in this paper was a selectively doped $\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As/GaAs}$ single interface heterojunction grown by molecular-beam epitaxy. The electron density N_s and the mobility μ of the sample at $T=4.2\,\mathrm{K}$ were $4.1\times10^{11}\,\mathrm{cm}^{-2}$ and $6.8\times10^{5}\,\mathrm{cm}^2/\mathrm{Vs}$, respectively. The sample was cut into a very long mesa ($W=50\,\mu\mathrm{m}$, $L=170\,000\,\mu\mathrm{m}$, $L/W=3300$), which was folded into an area of $4\times4\,\mathrm{mm}^2$, as schematically shown in Fig. 1(a). The back side of the sample was wedged by 3° to avoid an interference effect. Since all the previous experiments were performed by using fixed-wavelength FIR light sources with relatively high power (for example, molecular gas laser,[1–4] p-Ge laser[5]) and sweeping the magnetic field, it was difficult to develop detailed discussions on the electronic states of the 2DES's. In addition, such high-power light sources are likely to overheat the sample and hide subtle mechanisms. In the present work, a broadband black-body radiation from a mercury lamp was used as a weak FIR source. Fourier transform spectroscopy allowed us to perform swept-frequency measurements. Both the magnetic field and the FIR radiation were incident normal to the sample surface [Faraday geometry; Fig. 1(b)]. The sample was directly immersed in liquid He and all the measurements were performed at $T=4.2\,\mathrm{K}$. The sample was biased with a dc current I and ΔR_{xx} was detected by a lock-in technique. The photovoltaic component in the signal was canceled out by inverting the polarity of the bias current.

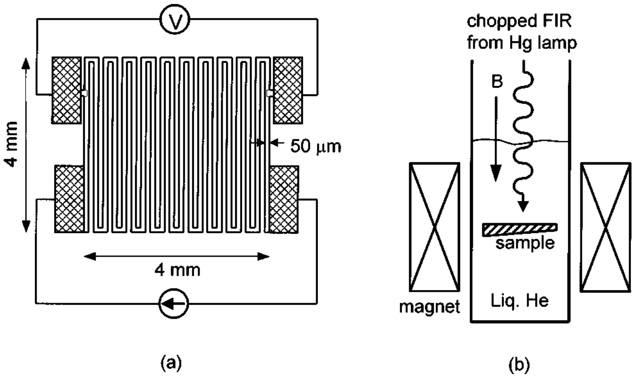


FIG. 1. Schematic illustrations of the sample geometry (a) and the measurement configuration (b).

Figure 2(a) shows the traces of R_{xx} of the 2DES measured at $T = 4.2\,\mathrm{K}$ with various excitation currents ($I = 0.12 - 12.0\,\mu\mathrm{A}$). As seen in the figure, R_{xx} on the higher-*B*-field side of the QHS's is essentially independent of *I*, which is expected for classical conductors. This fact indicates that the magnetoresistivity of the bulk 2DES dominates the sample resistance in this *B*-field region. In contrast, R_{xx} on the lower-field side of the QHS's is substantially reduced with decreasing *I*, which is understood to be due to the fact that the topmost Landau level is spatially separated from the lower occupied Landau levels by wide incompressible bands[11–13] and nonequilibrium edge channels shunt the bulk magnetoresistivity of the top Landau level.[6–11,14] In this *B*-field region, the sample resistance is governed not by the bulk magnetoresistivity but by the degree of equilibration between the edge channels and the partially filled topmost Landau level. Such nonequilibrium edge channel transport is quenched and the bulk magnetoresistivity recovers when the excitation current exceeds a few μA.[7,8,15]

The traces of ΔR_{xx} induced by a broadband FIR radiation chopped at 13 Hz are plotted in Fig. 2(b). At high bias currents ($I > 4.8\,\mu\mathrm{A}$), ΔR_{xx} of the order of several hundred ohms appears only in the close vicinity of the $\nu = 2$ and 4 QHS's. ΔR_{xx} has peaks on both higher- and lower-*B*-field sides of the QHS's and shows minima at exact integer fillings. A small structure is discernible also at $\nu = 6$ and 8. As *I* is reduced, while ΔR_{xx} on the higher-field side of the QHS's remains unchanged, ΔR_{xx} on the lower-field side of the $\nu = 2$ and 4 QHS's starts showing complicated behaviors; ΔR_{xx} first decreases with decreasing *I*. When *I* is further reduced, a peak shows up again at $B \sim 8\,\mathrm{T}$. Furthermore, negative ΔR_{xx} develops on the lower-field side of the $\nu = 2$ and 4 QHS's.

It has been considered that the origin of ΔR_{xx} is the rise in electron temperature induced by CR absorption.[1–5] In this mechanism, the photoinduced resistance change is expressed as

$$\Delta R_{xx} = (\partial R_{xx} / \partial T) \Delta T_e, \tag{1}$$

where ΔT_e is the rise in electron temperature induced by CR absorption, which is given by

$$\Delta T_e = P(\omega) \tau_e / C_e. \tag{2}$$

Here, $P(\omega)$ is the absorbed power of FIR radiation, τ_e the energy relaxation time, and C_e the specific heat of the 2DES, which is proportional to the density-of-states at the Fermi level. Since C_e becomes very small near the exact integer fillings, it is understandable that ΔT_e and, hence, ΔR_{xx} become significant only in the vicinity of the integer QHS's. To examine the validity of the electron heating model, ΔR_{xx} is compared with $\partial R_{xx} / \partial T$ in Fig. 3. As seen in Fig. 3(a), when nonequilibrium edge channel transport is quenched by passing a large dc bias current ($I = 12\,\mu\mathrm{A}$), ΔR_{xx} shows a trace similar to that of $\partial R_{xx} / \partial T$. For example, the double-peaked feature of ΔR_{xx} can be well explained by the *B*-field dependence of $\partial R_{xx} / \partial T$. The electron heating due to CR absorption is further supported by spectroscopic data on ΔR_{xx}. Figure 4 shows the excitation spectra of ΔR_{xx} measured for

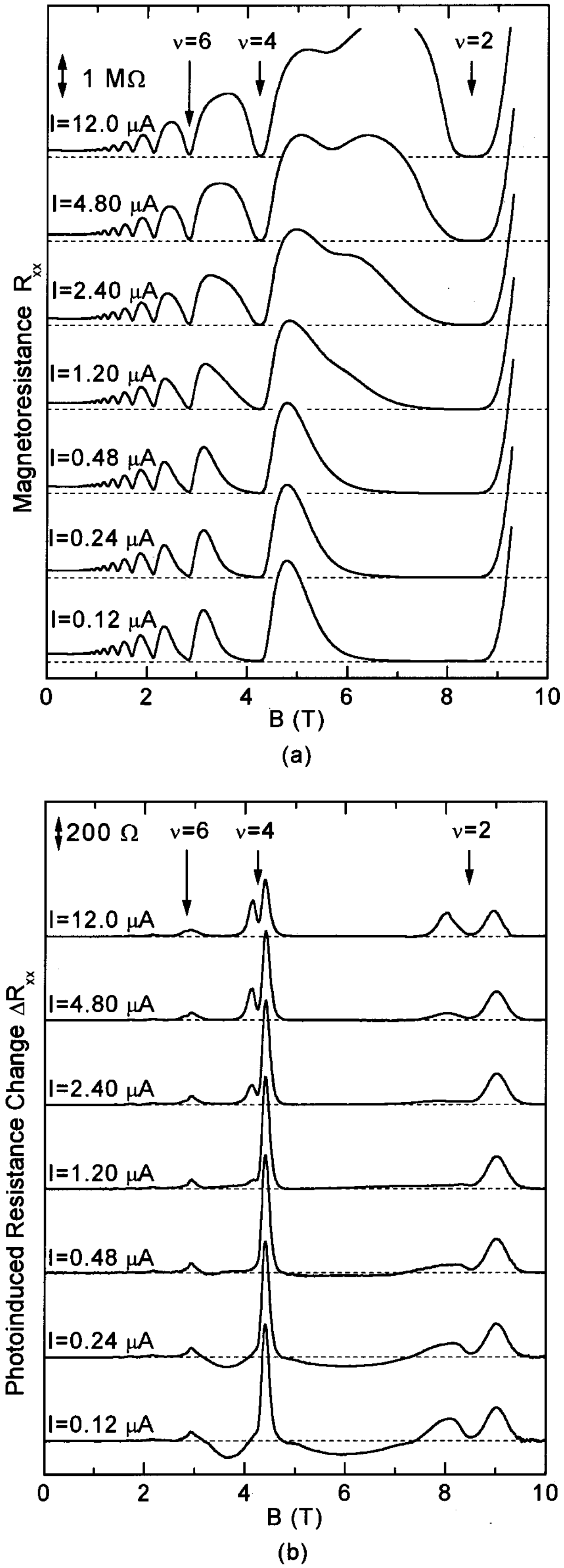


FIG. 2. The diagonal magnetoresistance R_{xx} (a) and photoinduced resistance change ΔR_{xx} (b) of the sample measured with various bias currents.

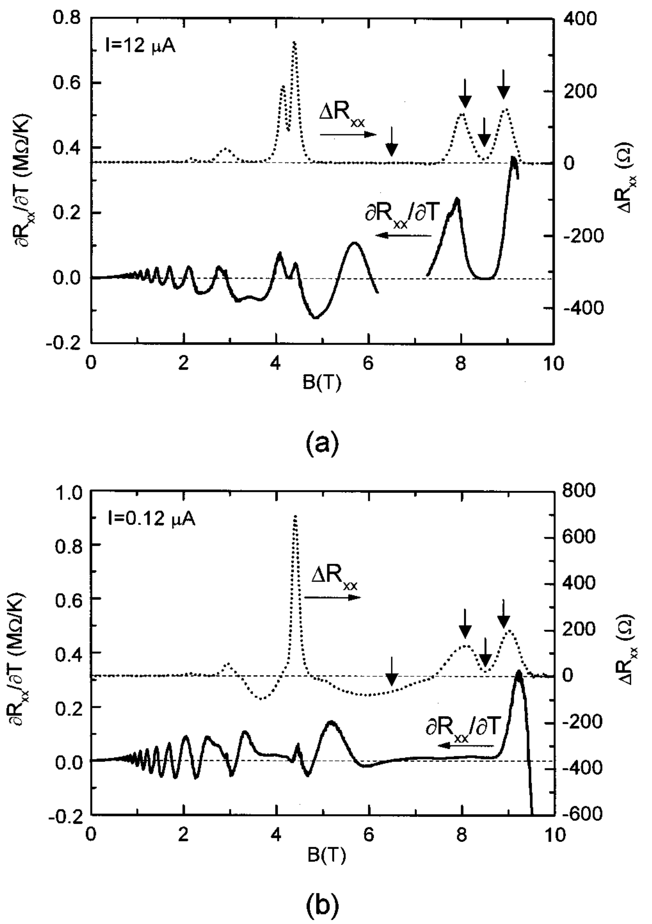


FIG. 3. Traces of ΔR_{xx} (dotted lines) and $\partial R_{xx}/\partial T$ (solid lines) measured with $I=12\,\mu$A (a) and 0.12 μA (b). $\partial R_{xx}/\partial T$ was obtained by subtracting two R_{xx} traces measured at $T=4.2$ and 3.9 K. The absence of data points between $B=6.1$ and 7.1 T for $I=12\,\mu$A is due to overload of the measurement instrument. The arrows in the figure indicate the magnetic-field positions where the excitation spectra of ΔR_{xx} were measured (see Fig. 4).

various excitation currents at representative magnetic fields. In the figure, also plotted are the FIR transmission spectra of the identical sample. It is found that all the ΔR_{xx} spectra measured for $I>4.8\,\mu$A, except for the case of $B=6.5$ T, have the same symmetric Lorentzian shapes as the FIR transmission spectra measured at the same B field. The full widths at half maximum (FWHM) of ΔR_{xx} are 1.8 cm^{-1}, which is consistent with the value expected for CR from N_s and μ of the 2DES. These facts indicate that when R_{xx} is dominated by the bulk magnetoresistivity of the partially occupied topmost Landau level, ΔR_{xx} is induced by electron heating due to CR absorption in the *bulk* 2DES.

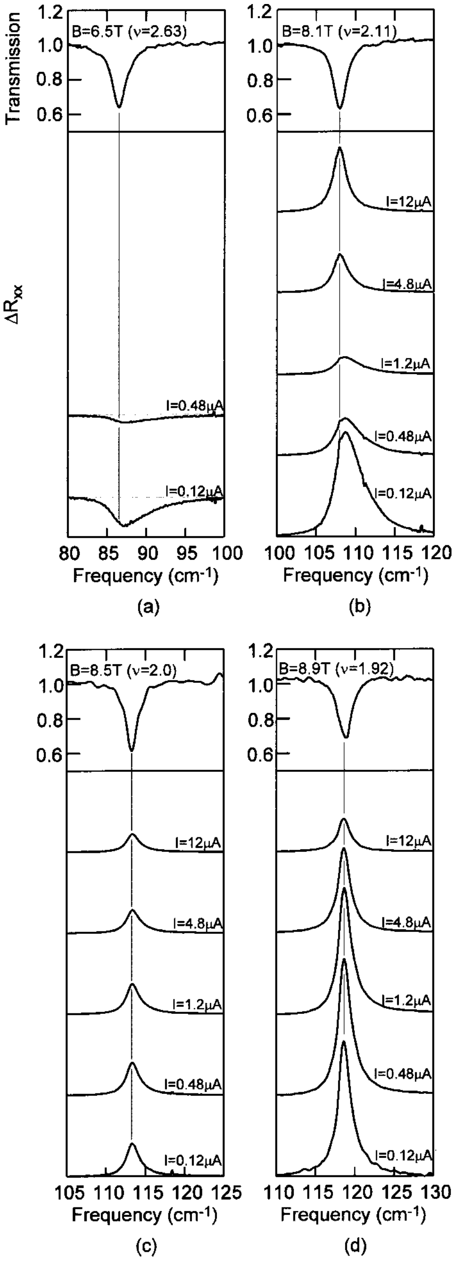
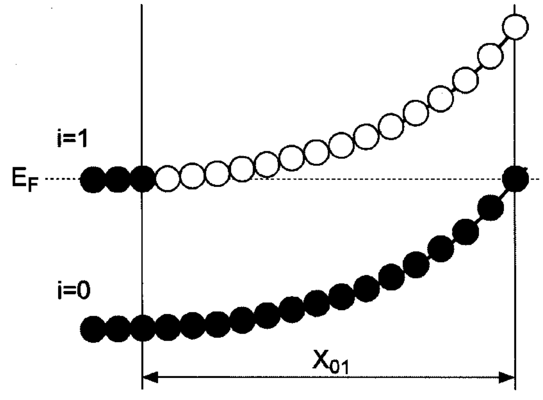


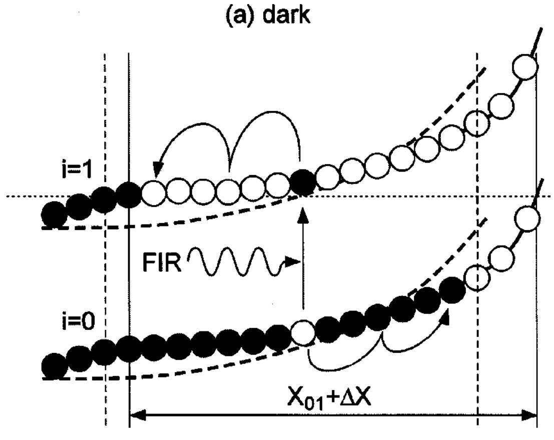
FIG. 4. Excitation spectra of ΔR_{xx} measured at $B=6.5$ T (a), 8.1 T (b), 8.5 T (c), and 8.9 T (d) for various bias currents by using a Fourier transform spectrometer. Also plotted in the figure are the CR transmission spectra of the identical sample.

When the bias current is reduced, however, the electron heating picture is found to break down. When I is reduced down to 0.12 μA [Fig. 3(b)], negative ΔR_{xx} is observed on the lower-field side of $\nu=2$ and 4 QHS's, even where $\partial R_{xx}/\partial T$ is slightly positive. Furthermore, ΔR_{xx} does not simply scale with $\partial R_{xx}/\partial T$; $\partial R_{xx}/\partial T$ on the lower-field side of the $\nu=2$ QHS is much smaller than that on the higher-field side, while the magnitudes of ΔR_{xx} are almost the same on both sides. These behaviors observed on the lower-B-field side of the QHS's are totally incompatible with the electron heating model.

To obtain a clue for the origin of ΔR_{xx}, we examined the ΔR_{xx} spectra in the low-bias current region. The excitation spectra of ΔR_{xx} measured at $\nu=2$ and 1.92 shown in Figs. 4(c) and 4(d), respectively, stay essentially unchanged even for small I, which suggests that ΔR_{xx} is induced by the electron heating due to CR absorption, as is the case for large I. However, dramatic changes are observed in the ΔR_{xx} spectra measured at $\nu=2.63$ and 2.11. The ΔR_{xx} spectra measured at $\nu=2.11$ [Fig. 4(b)] progressively becomes asymmetric with



(a) dark



(b) under FIR illumination

FIG. 5. A schematic energy band diagram near the sample edge in the dark condition (a) and under illumination (b). Full circles denote the states occupied by electrons and open circles represent unoccupied states.

decreasing *I*, showing a tail on the higher-frequency side. Furthermore, the peak positions are shifted by $\sim 1\ \mathrm{cm}^{-1}$ to a frequency higher than the bulk cyclotron frequency. The spectra of negative ΔR_{xx} measured at $\nu = 2.63$ [Fig. 4(a)] also show a high-energy tail and are shifted to the higher-frequency side. Since the sample resistance on the lower-field side of the QHS's at low current levels is governed by the nonequilibrium edge channel transport, the observed spectral shape of ΔR_{xx} reflects the dielectric properties of the edge region.[16] The spectroscopic measurements of ΔR_{xx} allow us a unique opportunity of probing the dielectric properties of the edge regions (FIR transmission measurements are not useful because edge states occupy only a negligibly small portion of the whole sample area in ordinary samples). A naive explanation for the shift of the excitation spectra of ΔR_{xx} from the bulk cyclotron frequency is that electrons experience an additional confinement potential due to the depletion field near the sample edges. However, full understanding of the observed unique spectral shape calls for further theoretical studies.

Noting that the magnetoresistance on the lower-field side of the integer QHS's is determined by the degree of equilibration between the resistive bulk and dissipationless edge channels,[14,15] we have attributed the negative ΔR_{xx} observed on the lower-field side of QHS's to the suppression of equilibration between the edge and bulk channels due to potential redistribution induced by the electron-hole pairs photoexcited near the sample edges. Figure 5 shows schematic energy band diagrams of the conducting channels near the sample edge. Because of a gradual confinement due to a soft edge depletion potential,[15–17] there is a finite spatial separation between the bulk and edge states, as denoted by X_{01} in Fig. 5(a). The degree of equilibration between the edge and bulk states strongly depends on X_{01}.[15] When electron-hole pairs are created by FIR radiation near the sample edge, the electrons are accelerated towards the interior side of the sample due to the depletion field and the holes move in the opposite direction. Such electron-hole spatial separation changes the local potential profile near the sample edge in such a way that the slope of the confinement field is reduced. Such a potential redistribution increases the spatial distance between the edge and the bulk channels by ΔX, as shown in Fig. 5(b), resulting in a reduction of equilibration between the edge and bulk channels. Although the origin of the positive ΔR_{xx} observed for small *I* near the $\nu = 2$ QHS is not clear at present, we speculate as follows; as the *B*-field approaches the exact integer filling, the topmost Landau level is progressively decoupled from the edge states and, consequently, the edge-bulk relaxation time increases exponentially. In such a case, the difference in nonequilibrium electrochemical potentials of the topmost Landau level and the edge states induced by photoexcitation may become as large as $\hbar\omega_c/2$ and further increase in the degree of nonequilibrium due to photoexcitation enhances the relaxation between edge and bulk states, leading to an increase in ΔR_{xx}.[8]

Finally, we would like to make a comment on the performance of the present device as a FIR photodetector. In general, it is not a trivial task to calibrate an absolute value of the responsivity of a FIR photodetector, because it is not easy to know the power of the FIR radiation that is incident on the detector in a cryogenic environment. In order to determine the responsivity of the quantum Hall FIR detector, we fabricated a standard broadband FIR source that can be operated in a cryostat.[18] This standard FIR source consists of

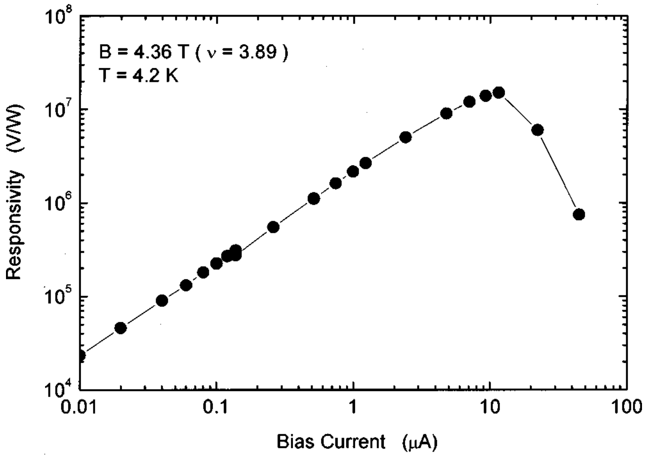


FIG. 6. The responsivity of the quantum Hall far-infrared photodetector calibrated at $B = 4.36$ T ($\nu = 3.89$) at $T = 4.2$ K is plotted as a function of the bias current *I*.

a NiCr film heater deposited on one side of a thin plate of a sapphire substrate. On the other side of the sapphire plate, a Au-doped Ge film was deposited. Since the resistivity of a Ge film with proper Au concentration is strongly temperature dependent, it was used as a thermometer. Because the spectrum of the black-body radiation is uniquely determined by the temperature and the emissivity of the NiCr heater, we can use it as a standard FIR source. By using this source, we first calibrated the responsivity of a Si bolometer mounted in the same cryostat. At the next step, we calibrated an absolute spectral intensity of the mercury lamp by the calibrated Si bolometer and a Fourier transform spectrometer. Finally, we calibrated the responsivity of the present quantum Hall FIR photodetector against the known spectral intensity of the mercury lamp.

The responsivity of the present quantum Hall device determined at $B=4.36\,\mathrm{T}$ ($\nu=3.89$) at $T=4.2\,\mathrm{K}$ is plotted in Fig. 6 as a function of the bias current I. The responsivity increases linearly with increasing I and reaches maximum at around $I=12\,\mu\mathrm{A}$. The maximum responsivity obtained for the present device was $2\times10^7\,\mathrm{V/W}$, which is already three orders of magnitude larger than that of commercially available bolometers operated at the same temperature. The observed FIR response of R_{xx} is, therefore, very promising for realizing sensitive, narrow-band FIR photodetectors. Further increase in I results in a reduction in responsivity. This is due to the fact that the electron heating by the bias current becomes significant in comparison with the heating by FIR radiation. A more detailed discussion on the performance of the quantum Hall FIR photodetector will be made elsewhere.[19]

In summary, we have investigated the FIR response of the diagonal magnetoresistance, R_{xx}, of the two-dimensional electron systems in the quantized Hall regime. It is found that ΔR_{xx} appears only in the vicinity of the quantum Hall states and that its magnitude and polarity strongly depends on the Landau-level filling factor ν. For $\nu<$even integer or large bias current, electron heating due to cyclotron resonance absorption in the bulk region is responsible for a positive ΔR_{xx}. For $\nu>$even integer and small bias current, however, ΔR_{xx} is induced by the change in the equilibration of the edge channel transport. We have also demonstrated that the observed photoresponse can be used for realizing very sensitive, narrowband FIR detectors. The maximum responsivity obtained for the present device was $2\times10^7\,\mathrm{V/W}$, which is three orders of magnitude larger than that of commercially available bolometers operated at the same temperature.

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