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Cyclotron-resonance-induced photovoltage of inversion electrons on GaAs

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We report a novel photovoltaic response occurring in gated AlAs-GaAs heterojunctions whenever inversion electrons absorb far-infrared radiation at cyclotron resonance. With radiation intensities below 1 mW/cm^2, photovoltages up to several mV are observed with the strongest signals around even Landau-level filling factors. The experiment can be described within the framework of carrier heating caused by resonantly absorbed far-infrared radiation. We present a simple model demonstrating that the photovoltage can be understood as reflecting the difference in the inversion electron chemical potentials at two different electron temperatures.

In gated heterojunctions on GaAs the gate potential can be significantly changed if the inversion electrons absorb far-infrared (FIR) radiation of sufficient intensity. Recently, a strong photovoltaic response has been reported to occur when two-dimensional (2D) plasmons resonantly absorb FIR radiation of intensity up to 5 kW/cm^2 generated by a free-electron laser.[1] Here we investigate a novel photovoltaic response of inversion electrons on GaAs in quantizing magnetic fields exposed to radiation of a FIR molecular gas laser. With FIR radiation intensities of typically below 1 mW/cm^2 photovoltages up to several mV can be observed at cyclotron resonance. The dependence of the photovoltage on electron density n_s, magnetic field strength B, and laser intensity is studied in detail. We find the sign and the magnitude of the photosignal to depend strongly on the filling factor $\nu = hn_s/eB$ of the Landau levels with strongest signals around even filling factors. Our experiment can be understood in the framework of carrier heating caused by the resonantly absorbed FIR radiation. We present a simple model demonstrating that the photovoltage can be described to reflect the difference in the electron chemical potentials at two different electron temperatures. A quantitative analysis of the photovoltage indicates a finite thermodynamic density of states (TDOS) between the Landau levels and yields a rise in electron temperature under FIR illumination of up to 10 K above the lattice temperature.

Our heterojunctions are grown by molecular-beam epitaxy on semi-insulating GaAs substrates. Above a GaAs buffer layer of about 2.4 μm, a short-period AlAs-GaAs superlattice of sixteen periods is grown. The AlAs and GaAs layer thicknesses are 2.0 and 1.6 nm, respectively. The eighth GaAs layer from the top is δ doped with Si to a concentration 1.25×10^{13} cm^{-2}. A 9.5-nm cap layer of doped GaAs completes the sequence. Diffused source and drain contacts are prepared to determine n_s via Shubnikov–de Haas oscillations of the magnetoresistance or magnetocapacitance measurements. As gate serves a semitransparent layer of NiCr with sheet resistance 0.5–1 k$\Omega/\Box$ evaporated on top of the sample. At liquid-helium temperature and gate voltage $V_g = 0$ we obtain a dc mobility around 5×10^5 cm^2/Vs and an electron density of $n_s = 3.5\times10^{11}$ cm^{-2}. The electron density varies nearly linearly with V_g and the conductivity threshold is at $V_g = -370$ mV.

The sample is mounted in front of a carbon-glass bolometer inside a waveguide system that is inserted into a helium cryostat at the center of a superconducting solenoid. Helium exchange gas cools the sample to a lattice temperature $T_L = 4.2$ K. The FIR radiation at wavelengths $\lambda = 393$, 163, and 118 μm is generated with a CO_2 laser-pumped molecular laser delivering intensities in the regime 1–10 mW/cm^2. Due to our experimental setup the intensities at the sample position are about 1 order of magnitude smaller and do not exceed 1 mW/cm^2. With the FIR radiation being chopped at frequencies 50 Hz $< f <$ 1000 Hz, we simultaneously record the ac gate-source voltage ΔV_g and the FIR transmission T with lock-in detection. The static gate voltage V_g is applied to the sample via a load resistor R_L obeying the condition $2\pi f \gg 1/R_L C_s$, where C_s is the sample capacitance.

Figure 1 compares the sample transmission T and the photovoltage ΔV_g at the laser wavelength 163 μm in B variation. In Fig. 1(a), cyclotron resonance is shown for $n_s = 2.4\times10^{11}$ cm^{-2} exhibiting a Lorentzian-type profile with an amplitude of 41% and a full width at half maximum of $\Delta B \simeq 0.1$ T centered at resonance magnetic field $B_c = 4.53$ T. Figure 1(b) depicts photovoltages ΔV_g measured at $n_s = 2.4\times10^{11}$ cm^{-2}, $n_s = 2.2\times10^{11}$ cm^{-2}, and $n_s = 2.0\times10^{11}$ cm^{-2}, respectively. Strong photosignals are observed only in a small magnetic field regime around B_c. Whereas the cyclotron resonance profile is nearly unaffected by changing n_s from 2.4 to 2.0×10^{11} cm^{-2}, the photosignal, however, changes dramatically, exhibiting a strong dependence on the Landau-level filling factor. In Fig. 1(b) the arrows mark the magnetic field positions $B_\nu = hn_s/\nu e$ with the Landau-level filling factor $\nu = 2$. The photosignal is negative and nearly symmetric at

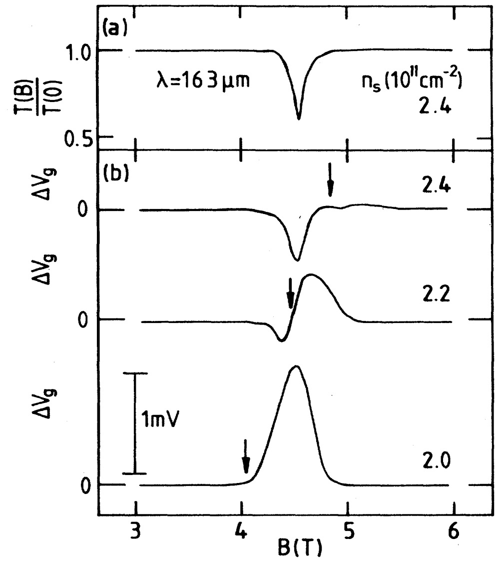

FIG. 1. (a) Cyclotron resonance at electron density $n_s = 2.4\times10^{11}$ cm^{-2} recorded in transmission T, and (b) photovoltages ΔV_g measured at different n_s. The laser wavelength is $\lambda = 163$ μm. The arrows mark magnetic fields $B_\nu = hn_s/\nu e$ with the Landau-level filling factor $\nu = 2$. The lattice temperature is $T_L = 4.2$ K.

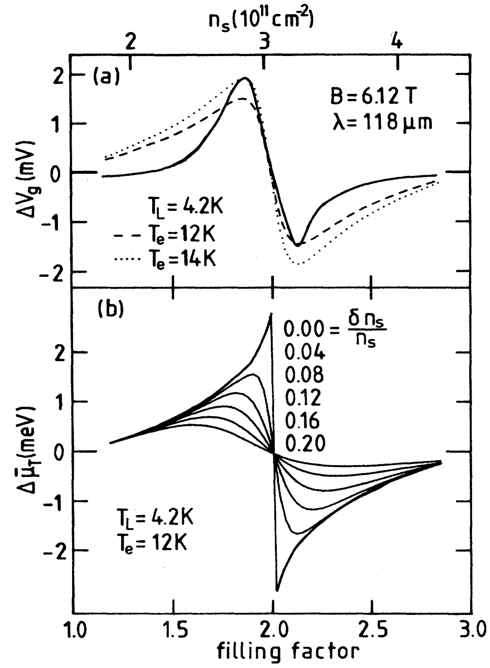

FIG. 2. (a) Photovoltage ΔV_g measured at cyclotron resonance ($\lambda = 118$ μm) vs Landau-level filling factor. The dashed and dotted curves are calculated gate-source potential differences as described in the text. (b) Calculated differences of the average electron chemical potentials $\Delta\bar{\mu}_T = \bar{\mu}(T_e) - \bar{\mu}(T_L)$ vs filling factor for different inhomogeneity parameters $\delta n_s/n_s$.

$n_s = 2.4\times10^{11}$ cm^{-2} ($B_\nu > B_c$), although considerably broader than the transmission signal. At $n_s = 2.2\times10^{11}$ cm^{-2} ($B_n \approx B_c$) the photovoltage exhibits a derivative-type line shape changing from negative to positive with increasing magnetic field strength. Finally, at $n_s = 2.0\times10^{11}$ cm^{-2} ($B_\nu < B_c$), we observe a symmetric photosignal which is positive. As indicated, typical signal strengths are of order mV.

The magnetic field sweep at various n_s, as in Fig. 1, demonstrates that the Landau-level filling factor ν is an important quantity governing the photosignal. However, an easier and more transparent insight into the basic mechanism causing the photosignal can be obtained from data measured in an n_s sweep at fixed magnetic field. In Fig. 2(a) the solid line shows the photovoltage measured at wavelength $\lambda = 118$ μm in an n_s sweep. The magnetic field strength B is fixed such that the resonance condition for cyclotron exitation $B = B_c$ is satisfied. Dashed and dotted curves are calculated photovoltages to be discussed in the following.

The resonantly absorbed FIR radiation at cyclotron resonance causes a nonequilibrium electron energy distribution, which, as a simplest approximation, we describe by a changed electron temperature T_e, or, equivalently, a changed chemical potential. In a heterojunction with a single subband occupied, as is the case here, the gate potential has been discussed before,[2-4] and using the notation of Ref. 2, may be written as

$$V_g = \frac{1}{e}\left[\mu - (E_s - E_0) + \frac{4\pi e^2 L}{\bar{\epsilon}} n_g + K_1\right].$$

Here μ is the electron chemical potential, E_s the depth of the potential well at the interface, E_0 the ground subband energy, n_g the gate charge density, and K_1 a quantity related to the band offset at the interface. To explain the observed photovoltage ΔV_g we will start with the assumption that the resonantly absorbed FIR radiation at cyclotron resonance solely changes the chemical potential while leaving all other quantities unaffected. We describe the nonequilibrium electron energy distribution under FIR illumination by an effective electron temperature T_e and calculate the photovoltage as

$$e\Delta V_g = \Delta\mu_T = \mu(T_e) - \mu(T_L). \quad (1)$$

In Fig. 2(b) we present a numerical calculation of $\Delta\mu$ for a homogeneous 2D channel, as indicated by $\delta n_s/n_s = 0$, covering the filling factor regime $1 < \nu < 3$. The electron and lattice temperatures are $T_e = 12$ K and $T_L = 4.2$ K, respectively, i.e., kT is small compared to the cyclotron energy $\hbar\omega_c$. In addition, the model calculation assumes a Gaussian profile of the Landau-level density of states with broadening parameter $\Gamma = 0.1$ meV small compared to the cyclotron energy $\hbar\omega_c$. In the extreme limit $\Gamma, kT_e \ll \hbar\omega_c$, Eq. (1) can be evaluated analytically in the vicinity of even filling factors $\bar{\nu} = 2,4,\ldots$

$$\Delta\mu_T = kT_e \operatorname{arcsinh}\left[\frac{\nu-\bar{\nu}}{4}\exp\left(\frac{\hbar\omega_c}{2kT_e}\right)\right] - kT_L \operatorname{arcsinh}\left[\frac{\nu-\bar{\nu}}{4}\exp\left(\frac{\hbar\omega_c}{2kT_L}\right)\right].$$

In general, $\Delta\mu_T$ increases with increasing temperature difference $\Delta T = T_e - T_L$ and increasing $\hbar\omega_c$. Assuming a homogeneous 2D system, the calculation reflects only qualitatively the measured photovoltage. The model calculation predicts an infinitesimal sharp jump in $\Delta\mu_T$ at filling factor $\nu = 2$ which, already at moderate $\Delta T \lesssim 10$ K, can be as high as $\hbar\omega_c/2$. Such a sudden change in ΔV_g is not observed experimentally. As long as adjacent Landau levels do not overlap, the inclusion of a finite Landau-level width will simply reduce $\Delta\mu$ but not affect the sharpness of the jump.

Experimentally, we find a steep but nevertheless gradual change in ΔV_g around $\nu = 2$. This suggests a finite TDOS between Landau levels. From the experimental gradient $d\Delta V_g/dn_s$, we estimate an upper bound in the background TDOS of about 9×10^9 cm^{-2}meV^{-1}. A finite TDOS between Landau levels has been deduced previously from specific heat,[5] magnetization,[6] and magnetocapacitance[7] measurements. The origin of this TDOS between Landau levels remains unclear. However, recently a statistical inhomogeneity model was proposed implying a finite TDOS between Landau levels.[2,8] To quantitatively explain our experiment we performed a numerical calculation of $\Delta\mu_T$ within the framework of this statistical model. Similarly, as in Ref. 8, we consider an inhomogeneous 2D channel, thus replacing $\Delta\mu_T$ by the statistical average $\Delta\bar{\mu}_T$. Our model calculation assumes a Gaussian distribution of the electron density with a constant inhomogeneity parameter $\delta n_s/n_s$. Results are presented in Fig. 2(b) with $\delta n_s/n_s$, as indicated. The calculated $\Delta\bar{\mu}_T$ reflect well the features of the experimental ΔV_g. In particular, it describes the gradual change of ΔV_g around $\nu = 2$. Best fits to the experiment [Fig. 2(a)] are obtained with parameters $\delta n_s/n_s \simeq 5\%$ and electron temperatures T_e under FIR illumination ranging from 12 to 14 K. To support our analysis of the photovoltage and to independently verify the electron temperature under FIR illumination, we measured the magnetoresistance of the sample at different lattice temperatures. Comparing FIR radiation-induced changes of the magnetoresistance minimum at $\nu = 2$ for fixed $T_L = 4.2$ K with these data, we obtain an indication of the electron temperature consistent with the analysis of the photovoltage.

The above calculations predict photovoltages too high compared to the experiment for filling factors that are not in close proximity to $\nu = 2$. This is caused by the fact that the experiment is carried out at constant laser intensity I and not at constant electron temperature. One has to consider that the 2D electron specific heat C_v,[5,9] is an oscillatory function of the magnetic field strength and depends on the filling factor. Thus at given I the change of electron temperature ΔT will depend on the filling factor as $\Delta T \propto I/C_v$. At low temperatures the electron heating is less effective if μ is close to the center of a Landau level, since C_v will be large for odd but small for even ν. This implies that varying n_s or ν in the experiment does not conserve the rise in electron temperature. To illustrate this we show in Fig. 3(a) the dependence of the photovoltage ΔV_g on laser intensity I at different filling factors in close proximity to $\nu = 2$. Generally the photovoltage increases with intensity. However, the increase depends on

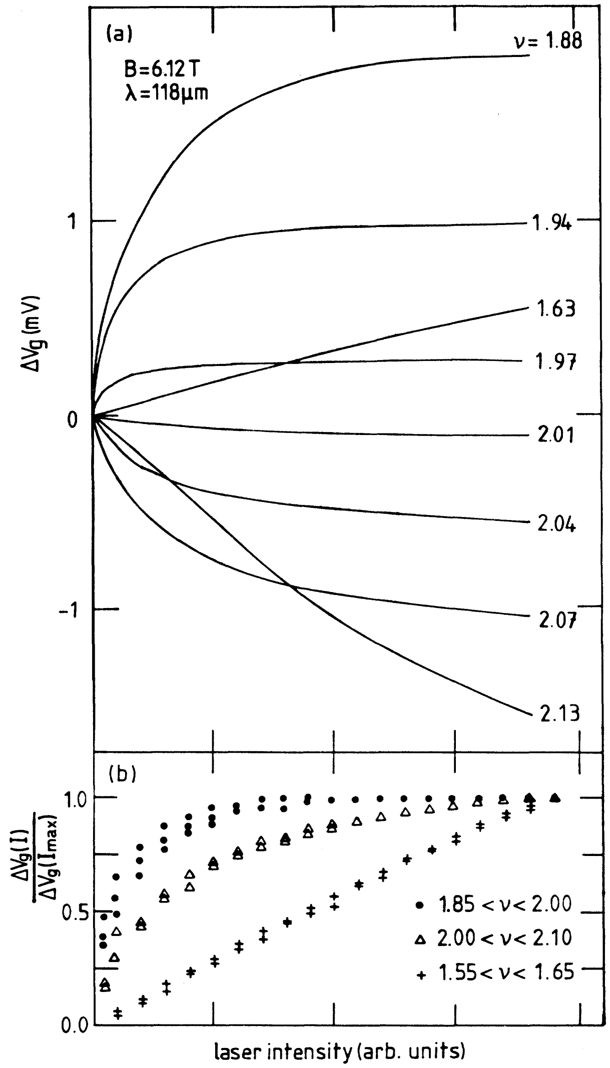

FIG. 3. (a) Dependence of the photovoltage on FIR laser intensity at various Landau-level filling factors close to $\nu = 2$. (b) Normalized photovoltages $\Delta V_g(I)/\Delta V_g(I_{\max})$ vs laser intensity for different filling factor regimes.

ν and ΔV_g easily saturates at ν close to 2. In Fig. 3(b), the normalized photovoltages $\Delta V_g(I)/\Delta V_g(I_{\max})$ are shown for various filling-factor regimes. For filling factors in close proximity to $\nu = 2$, i.e., small C_v, signal saturation is achieved at relative low laser intensities, whereas for ν outside this range, a linear relation with laser intensity is observed.

Our experiment can be well described by the statistical inhomogeneity model assuming a single-particle density of states with Landau-level width small compared to $\hbar\omega_c$. The calculation yields a TDOS of $dn_s/d\mu \simeq (4-6)\times10^9$ cm^{-2}meV^{-1} around $\nu = 2$ in the temperature regime 4.2 K $\leq T_e \leq$ 14 K. Eventually, our experiment might contribute to the understanding of nonlinear screening behavior[10,11] that is believed to be present in inhomogeneous 2D systems in high magnetic fields.

In conclusion, a novel photovoltaic response is observed for electron inversion layers on GaAs. FIR radiation intensities below 1 mW/cm^2 absorbed at cyclotron resonance give rise to changes in the gate-source potential exceeding mV. The experiment is explained within the framework of electron heating due to the absorbed FIR radiation. The analysis of the photosignal emphasizes the importance of inhomogeneity in n_s and a finite TDOS between the Landau levels. Electron temperatures obtained with moderate FIR intensities vary with the filling factor and can exceed the lattice temperature by up to 10 K. Our experiment demonstrates that FIR laser spectroscopy of cyclotron resonance excitation on 2D systems has to be viewed with caution since it yields large changes of the electron temperature near filling factors where the electron specific heat has minima. Our photovoltaic experiments suggest a sensitive method to measure the density of states and might be used as well for creating a new, fast, tunable, and sensitive FIR detector.

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