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Fast terahertz detectors with spectral tunability based on quantum Hall Corbino devices

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We present THz photoconductivity measurements on Corbino-shaped GaAs/AlGaAs heterostructures. The THz source is a pulsed *p*-Ge laser, which provides photon frequencies of 1.7 THz to 2.5 THz (corresponding to wavelengths of 180–120 μm). We investigate the relaxation process from the dissipative state to the quantum Hall state time-resolved and find that the relaxation time depends on the applied voltage and on the mobility of the sample. Relaxation times of approximately 10 ns to over 200 ns are observed. A simple picture is suggested to explain the results. In addition, spectrally resolved measurements are discussed. The short response time and the useful spectral selectivity together with the high sensitivity make QH devices promising for high-performance THz detectors. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2061863]

For various regions of the spectrum of electromagnetic waves, high performance sources and detectors are available. However, this is not the case for the Terahertz (THz) range. This far infrared range is defined by frequencies from about 0.5 THz to 10 THz, corresponding to wavelengths of approximately 500 μm to 25 μm.

Many THz applications in material research, in atmospherical and astronomical observations and in the analysis of biological systems have stimulated an intense research in the field of THz wave generation and detection, see Refs. 1–4, and references therein. Both the generation and detection of THz radiation are rather difficult due to the upper frequency limit of electronic devices of some 100 GHz and upper wavelength limit of "usual" optics to about 100 μm. Detectors for frequencies around 1 THz commonly utilize the bolometer effect, usually having no spectral resolution. Hot electron bolometers can respond on the nanosecond time scale, and superconducting bolometers can be very sensitive. However, detectors which combine fast response, high sensitivity and spectral selectivity are difficult to realize.[2,5]

Quantum Hall (QH) systems[6] can be used as THz detectors (see also e.g. Refs. 7 and 8). The radiation causes a breakdown of the QH state into a dissipative state. This method allows to realize highly sensitive detectors (responsivity of $1.1\cdot 10^7$ V/W, detectivity of $4.0\cdot 10^{13}$ cm Hz$^{1/2}$/W, at 4.2 K).[9] The process works best under cyclotron resonance conditions, i.e. if the photon energy fits to the Landau gap.[10] Thus the detector can be spectrally tuned.

In this study, we present time-resolved photoconductivity measurements on Corbino-shaped QH detectors. A pulsed *p*-Ge laser is used as the THz source. We find fast relaxation times τ and a dependence of τ on the applied source-drain voltage V_{SD}. We suggest an explanation for this dependence. In addition, we present spectrally resolved measurements. We find that the Corbino devices possess faster response times and a better spectral resolution in comparison to detectors made in meander geometry, investigated earlier.[11]

The THz radiation source used in this study is a *p*-type germanium laser ($p\approx 10^{19}$ m^{-3}), operating on the basis of inter-Landau level transitions of light holes in the wavelength range from 120 μm to 180 μm.[12] The laser emits about one pulse per second with a duration adjustable by the electrical pumping source between 0.3 and 50 μs. The decay time of the laser pulse $\tau_{laser}\leqslant 20$ ns (measured with a *p*-Ge detector) is determined by the switch-off flank of the used high power FET-based electrical pumping source.

The investigated detector samples are MBE grown GaAs/AlGaAs heterojunctions with a two-dimensional electron system (2DES). The samples are patterned in Corbino geometry (circular ring shaped 2DES confined by metallic contacts) with a large photoactive area (inner and outer radius: 500 μm and 1500 μm). The sample properties are summarized in Table I. The electron concentration is tunable by a gate voltage.

The laser system (THz source) and the QH-sample (THz detector) are mounted in the same He bath cryostat (*T*

TABLE I. Sample properties. The denoted mobilities are given by measurements at Hall bar structures using the same wafer. The QH breakdown voltage V_c for the sample No. 8788 was 4 V during the time dependent measurements, as noted in the table, but 3 V in an earlier cooling cycle.

Sample No.	Electron concentration (m^{-2})	Mobility (T^{-1})	QH breakdown voltage (V)
8447	2.7×10^{15}	10	6.25
8788	2.0×10^{15}	50	4
8815	1.9×10^{15}	150	2

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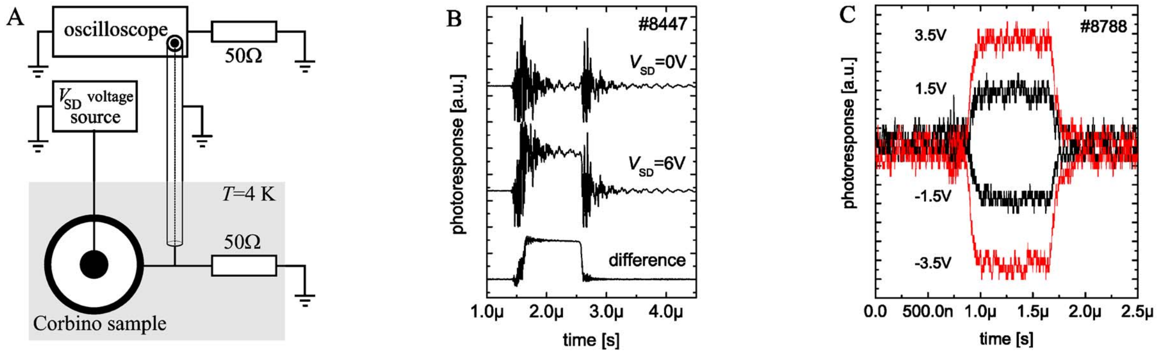

FIG. 1. Time-resolved measurements: (A) Circuitry; (B) raw time-resolved PR and difference signal; (C) examples for time-resolved PR measurements at different V_{SD} voltages (denoted near the curves).

$\approx$4 K). They are connected by a brass tube, which serves as a waveguide for the THz radiation. The magnetic fields are generated by superconducting coils.

The measurements are performed near the filling factor $\nu=2$ of the QH-sample (sample magnetic field B around 5 T). The detector circuitry is shown in Fig. 1(a). In the Corbino geometry the azimuthal part of the electric field is zero and the source-drain current I_{SD} is proportional to the longitudinal conductivity σ_{xx}: $I_{SD}\propto j_{SD}=\sigma_{xx}E_{SD}$. The photoresponse (PR) corresponds to $\Delta I_{SD}\propto\Delta\sigma_{xx}$, which is the difference of I_{SD} with and without illumination. I_{SD} is measured as a voltage over a serial resistor. For the time-resolved measurements the signal is transfered by a coaxial cable to a digital oscilloscope. This cable is usually terminated by 50 Ω resistors for impedance matching.

In the raw time dependent PR we find strong disturbances after switching the laser on and off. This is due to electric coupling between the high power laser supply cable and the detector cable and is not completely avoidable by the cable shielding. To avoid this problem we use reference measurements at $V_{SD}=0$ and calculate the difference between the signal at $|V_{SD}|>0$ and $V_{SD}=0$. Typical results are shown in Figs. 1(b) and 1(c). The switch-on of the laser radiation causes a fast increase of the PR signal. During the illumination the PR stays constant. Finally the switch-off of the radiation causes fast relaxation of the PR.

From fitting the decay of the PR by a function of the type $\exp(-t/\tau)$ we obtained the relaxation time τ as a function of V_{SD}. The results are shown in Fig. 2. Tendentially we see faster relaxation for the low mobility samples. For the samples Nos. 8788 and 8447, we find a distinct maximum of $\tau=110$ ns and $\tau=20$ ns, respectively, at voltages slightly below the corresponding breakdown values V_c. Sample No. 8815 shows a decrease of τ for $V_{SD}>1$ V.

In the following section a possible explanation is given. What we consider is the time τ for the relaxation process from a dissipative state to the QH state. For the low mobility samples Nos. 8788 and 8447 the maximum in τ is near the breakdown voltage V_c. Thus for voltages below V_c there is an increase of τ with V_{SD}. This can be explained qualitatively with the heating effect of the dissipative current I_{SD}: For high voltages close to V_c (but still beneath), I_{SD} and the heating effect are relatively high. Thus for a relatively long time the dissipative state stays and is stabilized by itself. At lower voltages this heating feedback is less pronounced, leading to shorter relaxation times. For voltages beyond V_c there is no QH state and therefore the relaxation process is fast. Sample No. 8815 which has the highest mobility shows a different behavior (see Fig. 2): The QH state seems to be more stable at low voltages, because we find there a longer relaxation.

The measured relaxation time scales are comparable to those reported in Ref. 13 (around 10 ns, estimated by an indirect method). Earlier published measurements similar to ours on meander type detectors,[9,11] show time scales several orders of magnitude longer. Therefore Corbino-shaped detectors are suitable for fast detectors (see above).

The properties of our detectors can be tuned by the V_{SD} voltage. Because the sensitivity is best in the QH region and increases with increasing V_{SD} and the response times becomes worse with increasing V_{SD}, a certain V_{SD} should be chosen for a designated application.

Furthermore, we investigate the spectral selectivity. At fixed laser energy E_{photon} we measure the PR while tuning the sample. At cyclotron resonance (CR) conditions $E_{photon}=\hbar\omega_c$ (with $\omega_c=eB/m^*$, elementary charge e and effective mass m^*) the highest PR is found, decaying to both sides of the CR. These data are fitted by a Lorentzian function in the form $\Gamma/(4(E-E_{photon})^2+\Gamma^2)$ with the full width at half maximum Γ. Γ corresponds to the spectral resolution. The results are shown in Fig. 3. We find Γ in the range from 1 to 2.5 meV, and the highest Γ value was found for the sample with the lowest mobility.

To summarize, the THz photoconductivity of QH Corbino samples was investigated. A pulsed laser with very fast switching times and an impedance-matched detector cir-

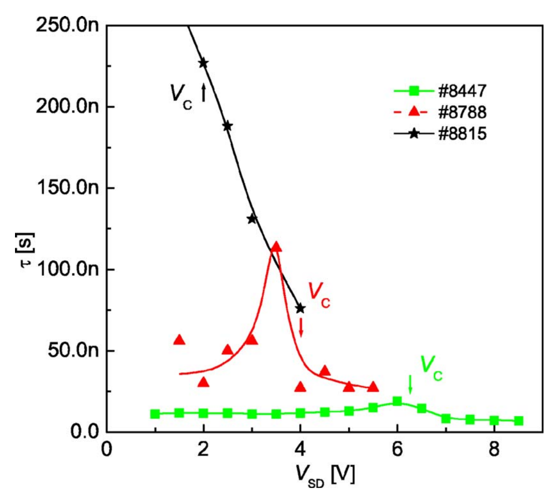

FIG. 2. Relaxation time τ vs source-drain voltage V_{SD} for different samples. The breakdown voltages V_c are marked.

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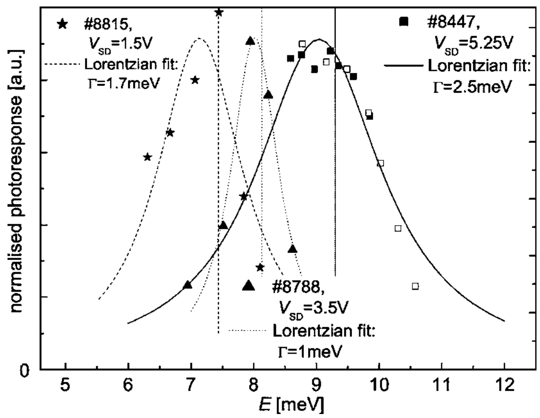

FIG. 3. Spectral response at $V_{SD} \approx V_c$: The data points are taken from PR vs B traces, measured at different electron concentrations (tuned by a gate voltage). The data points correspond each to the same filling factor ν, near $\nu=2$. For more details concerning this method, see Ref. 10. For sample No. 8447 the points are taken at the left and right flank (filled and unfilled points) of the QH plateau. To estimate Γ a Lorentz fit is made. Sample No. 8815 shows an asymmetric behavior, therefore the fit does not match as well as for the other samples. The laser photon energies (different for all examples) are marked as vertical lines in the diagram.

cuitry allows us to resolve intrinsic time scales. We find a dependence of the relaxation time τ on the source-drain voltage V_{SD}. The fastest times, $\tau \leq 20$ ns, are found for the sample No. 8447. In addition, we measured the spectral resolution of the QH samples. We find the best spectral resolution, $\Gamma = 1$ meV, for the sample No. 8788. Thus QH detectors combine high sensitivity with fast response time and useful spectral selectivity.

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