Fast detector of the ellipticity of infrared and terahertz radiation based on HgTe quantum well structures

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We report a fast, room temperature detection scheme for the polarization ellipticity of laser radiation, with a bandwidth that stretches from the infrared to the terahertz range. The device consists of two elements, one in front of the other, that detect the polarization ellipticity and the azimuthal angle of the ellipse. The elements respectively utilise the circular photogalvanic effect in a narrow gap semiconductor and the linear photogalvanic effect in a bulk piezoelectric semiconductor. For the former we characterized both a HgTe quantum well and bulk Te, and for the latter, bulk GaAs. In contrast with optical methods our device is an easy to handle all-electric approach, which we demonstrated by applying a large number of different lasers from low power, continuous wave systems to high power, pulsed sources.

INTRODUCTION

Fast and easy recording of the state of polarization, i.e. measurements of the Stokes parameters of a radiation field is of great importance for various applications in science and technology. In particular the ellipticity of transmitted, reflected or scattered light may be used to analyze the optical anisotropy of a wide range of media. The established method for gaining information about the polarization state of light is the use of optical elements to determine optical path differences. Recently we presented a new technique which allows all-electric room temperature detection of the state of polarization providing full characterization of laser beams at THz frequencies. The operation of the detector system is based on photogalvanic effects in semiconductor quantum well (QW) structures of suitably low symmetry. The detection principle has been demonstrated on doped GaAs and SiGe QWs at room temperature applying terahertz molecular lasers as radiation sources. The time constant of photogalvanic currents is determined by the momentum relaxation time of free carriers which is in the range of picoseconds at room temperature. This makes possible to measure the state of polarization of laser radiation with sub-nanosecond time resolution. Here we report a substantial improvement of the sensitivity of the method, by about two orders of magnitude higher compare to those previously reported in GaAs QWs, and on the extension of the detector’s spectral range from terahertz to the mid-infrared in a single device. To achieve these goals we studied photogalvanic effects in QWs prepared from the narrow gap semiconductor HgTe and also analyzed bulk single-crystalline Te and GaAs. HgTe QWs are novel promising narrow gap materials characterized by high electron mobilities, low effective masses, an inverted band structure, large g-factors, and spin-orbit splittings of sub-bands in the momentum space. Because of these features low dimensional HgTe/CdHgTe structures hold a great potential for detection of terahertz radiation and for the rapidly developing field of spintronics. The most important property of the materials relevant for the detection of the radiation ellipticity is the magnitude of the circular photogalvanic effect (CPGE) which gives access to the helicity of a radiation field. Therefore we focus our work on the study of the CPGE. We show that HgTe QWs can be used for all-electric detection of radiation ellipticity in a wide spectral range from far-infrared (terahertz radiation) to mid-infrared wavelengths. The detection is demonstrated for various low power cw and high power pulsed laser systems. A large spectral range was covered by low-pressure cw, pulsed, and Q-switched CO2 lasers and high-power pulsed transverse excited atmospheric pressure (TEA) CO2 lasers, which are used directly in the infrared range or as pump sources for THz molecular lasers. In addition measurements were carried out with a free-electron-laser making use of its tunability and short pulses.

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EXPERIMENTAL

The experiments were carried out on Cd$_{0.7}$Hg$_{0.3}$Te/HgTe/Cd$_{0.7}$Hg$_{0.3}$Te single QWs of 21 nm width. The structures were grown on GaAs substrates with surface orientation (013), by means of a modified Molecular Beam Epitaxy method [18]. Samples with electron densities of $9 \times 10^{11}$ cm$^{-2}$ and mobility $2.5 \times 10^4$ cm$^2$/Vs are studied at room temperature. We used square shaped samples of 5 × 5 mm$^2$ size. Two pairs of contacts (along directions x and y) was centered in the middle of cleaved edges parallel to the intersection of the (013) plane and cleaved edge face {110} (see the inset to Fig. 1). To demonstrate the detector operation in the mid-infrared spectral range we used a Q-switched CO$_2$ laser covering the spectrum from 9.2 to 10.8 µm with peak power $P$ of about 1 kW and pulsed TEA-CO$_2$ laser generating single 100 ns pulses of power up to 100 kW [3]. Besides gas lasers we used the output from the free electron laser “FELIX” at FOM-Rijnhuizen in the Netherlands at wavelengths between 5 µm and 17 µm and power about 100 kW [19]. Making use of the frequency tunability and short pulse duration of this laser we obtain the spectral behaviour of the detector responsivity and demonstrated its time resolution. The output pulses of light from FELIX were chosen to be ≈ 3 ps long, separated by 40 ns, in a train (or "macropulse") of duration of 7 µs. The macropulses had a repetition rate of 5 Hz. For optical excitation in the terahertz range we used a cw optically pumped CH$_3$OH laser with radiation wavelength of 118 µm and power $P$ of about 10 mW and high power pulsed optically pumped NH$_3$, D$_2$O, and CH$_3$F lasers [3]. Several lines of the pulsed laser with power ranging from 100 W to 100 kW in the wavelength range between $\lambda = 76$ µm and 496 µm have been applied.

To vary the ellipticity of the laser beam we used $\lambda/4$ plates made of x-cut crystalline quartz in the terahertz range and a Fresnel rhomb in the mid-infrared. The light polarization was varied from linear to elliptical. Rotating the polarizer varies the helicity of the light, $P_{circ} = \sin 2\varphi$, from $P_{circ} = -1$ (left-handed circular, $\sigma_-$) to $P_{circ} = +1$ (right-handed circular, $\sigma_+$) where $\varphi$ is the angle between the initial linear polarization and the optical axis (c-axis) of the polarizer. In Fig. 1 (top) the shape of the polarization ellipse and the handedness of the radiation are shown for various angles $\varphi$.

Photogalvanic effects applied here for radiation detection generate an electric current which we measure in homogeneously irradiated unbiased samples. The current is converted into a signal voltage by load resistors. The signal voltages were picked up from the detector across a $R_L = 50$ Ω load resistor for short radiation pulses. For cw irradiation we use a load resistance of 1 MΩ, which is much higher than the sample resistance. For pulsed lasers the signals were fed into amplifiers with voltage amplification by a factor of 100 and a bandwidth of 300 MHz and were recorded by a digital broad-band (1 GHz) oscilloscope. For time resolved measurements the signal was picked up directly from the sample without amplification. For detection of cw laser radiation we modulated our beam with a chopper at modulation frequency 225 Hz and used a low-noise pre-amplifier (100 times voltage amplification) and a lock-in-amplifier for signal recording. We note that in this low modulation frequency case the high time resolution of the set-up is not required.

DETECTION OF THE HELICITY APPLYING HgTe QWs

With illumination of HgTe samples at normal incidence we detected in the in-plane x-direction a helicity dependent current signal. This is shown in Fig. 1 for a measurement at room temperature obtained at 77 µm wavelength of a pulsed NH$_3$ laser. Note that the measurement is d.c. coupled and no background subtraction has occurred. The signal changes direction if the circular polarization is switched from left to right-handed ($\sigma_-$ to $\sigma_+$ as shown in Fig. 1) and vice versa. The helicity dependence and in particular the change of sign demonstrate that the observed current $j_x$ is due to the CPGE [3]. The voltage signal resulting from the photocurrent $V_x \propto j_x$ is well described by

$$V_x^{\text{HgTe}} = S(\omega) P \cdot P_{circ},$$

where $S(\omega)$ is the responsivity of the detector at frequency $\omega$. The term $P_{circ}$ represents the circular polarization of the incident light. The factor $S(\omega)$ depends on several aspects such as the detector material, the wavelength of the laser, and the alignment of the detector elements.
where $S(\omega)$ denotes the strength of CPGE at radiation frequency $\omega$, and, consequently, the sensitivity of this detector unit. The photogalvanic current is described by the phenomenological theory. It can be written as a function of the electric component of the radiation field $E$ and the propagation direction $\hat{e}$ in the following form \[17\]

$$j_\lambda = \sum_\rho \gamma_\lambda \rho P_{circ} |E|^2 + \sum_{\mu,\nu} \chi_{\lambda\mu
u}(E_\mu E_\nu^* + E_\mu^* E_\nu), \quad (2)$$

where the first term on the right hand side is proportional to the helicity or circular polarization degree $P_{circ}$ of the radiation represents the CPGE while the second term corresponds to the linear photogalvanic effect (LPGE) \[2\] which may be superimposed to the CPGE. The indices $\lambda$, $\rho$, $\mu$, $\nu$ run over the coordinate axes $x$, $y$, $z$. The second rank pseudotensor $\gamma_\lambda \rho$ and the third rank tensor $\chi_{\lambda\mu\nu}$ symmetric in the last two indices are material parameters. The (013)-oriented QWs belong to the trivial point group $C_1$ lacking any symmetry operation except the identity. Hence symmetry does not impose any restriction on the relation between irradiation and photocurrent. All components of the tensor $\chi_{\lambda\mu\nu}$ and the pseudotensor $\gamma_\lambda \rho$ may be different from zero. Equation \[2\] yields for normal incidence of the radiation the angle $\varphi$ dependence of the photosignal $V_x \propto j_x$:

$$V_x/P = S(\omega) \sin 2\varphi + b(\omega) \sin 4\varphi + c(\omega) \cos 4\varphi + d(\omega), \quad (3)$$

where $S(\omega)$, $b(\omega)$, $c(\omega)$, and $d(\omega)$ can be consistently expressed by components of the tensors $\gamma_\lambda \rho$ and $\chi_{\lambda\mu\nu}$ determined in Eq. \[2\] \[20\]. While at most wavelengths we found that the first term in Eq. \[3\] dominates (see Fig. \[1\]), at some wavelengths we also find a small polarization independent current offset and a slight distortion of the sine-shape of the $V_x$ versus $\varphi$ curve. This deviation from the $2\varphi$ behaviour is demonstrated in the inset of Fig. \[2\] for 118 $\mu$m wavelength of the $cw$ CH$_3$OH laser. The solid line in this inset is calculated after Eq. \[3\] yielding a good agreement to the experiment. Note, however, that for a technical application as an ellipticity detector described here it is desirable to have samples with dominating CPGE term being simply proportional to $P_{circ}$ like the photoresponse in Fig. \[1\]. For all wavelengths this goal could be achieved by using technologically available (112)-grown samples \[6\]. The reason is the higher symmetry of such structures. In (013)-oriented samples investigated in our work the CPGE current can have arbitrary direction and, in fact, the projection of the current on the connecting line between the contacts is measured. Furthermore three LPGE current contributions are allowed due to the low symmetry of the samples. In contrast, in (112)-grown structures the current direction for normal incidence is bound to the [110]-crystallographic direction. This is because such samples belong to the $C_s$ point group forcing the CPGE current to a direction...
normal to the mirror reflection plane. This feature makes the preparation of samples with dominating CPGE for all wavelengths possible. Picking up the signal from [110]-
direction should increase the sensitivity and smoothen the spectral dependence.

In Fig. 2 and Fig. 3 the spectral dependence of the CPGE is shown for the infrared and THz ranges, respectively. The measurements are carried out at room temperature at normal incidence of radiation and for circularly polarized radiation ($\varphi = 135^{\circ}$) where the CPGE signal is maximal. In the THz range molecular lasers were applied while the measurements in the infrared range were performed using FELIX (open circles in Fig. 3) and a Q-switched CO$_2$ laser (full circles in Fig. 3). In the infrared range CPGE in HgTe QWs does not show much dispersion for $\lambda$ between 8 and 14 $\mu$m while in the THz range the photocurrent rises significantly with increasing wavelength. The spectral behaviour of the signal is mainly caused by the mechanism involved in the radiation absorption, interband in the mid-infrared range and Drude-like in the terahertz range. The sensitivity in the mid-infrared range being of the order of 80 mV/kW is comparable with that of photon drag detectors widely applied for detection of infrared laser radiation [4, 21, 22]. Comparing sensitivities of HgTe QW and GaAs QW devices in the THz range we obtain that a detector element made of one single HgTe quantum well ($S = 10$ mV/kW for $\lambda = 148$ $\mu$m) has about 100 times higher sensitivity per quantum well than devices based on GaAs QWs [23].

The sensitivity of HgTe QW based devices can be further improved simply by using a larger number of QWs.

To determine the time resolution of our device we used 3 ps pulses of FELIX. The left inset in Fig. 4 shows that the response time is at most 100 ps. We attribute the observed time constant to the bandwidth of our electronic set-up. A fast response is typical for photogalvanics where the signal decay time is determined by the momentum relaxation time [2, 17] being in our samples of the order of 0.3 ps at room temperature. As a large dynamic range is important for detection of laser radiation, we investigated the dependence of the sensitivity of the detection system on the radiation intensity applying $c.w.$ and high-power pulsed radiation. We observed that the ellipticity detector at homogeneous irradiation of the whole sample remains linear up to 2 MW/cm$^2$ over more than nine orders of magnitude.

In a further experiment we checked the variation of the sensitivity due to a deviation from normal incidence of radiation. Measurements at oblique incidence demonstrate that the CPGE current attains maximum at normal incidence. This is shown in Fig. 4 for angles of incidence $\theta_0$ in the range $\pm 30$ degrees at a wavelength $\lambda = 148$ $\mu$m and for circularly polarized light. We find that the sensitivity is reduced at a deviation from normal incidence. This behaviour follows from Eq. [2] yielding $j \propto t_p t_s \cos \theta$ where $t_p$ and $t_s$ are the Fresnel transmission coefficients for $s$- and $p$-polarized light, and $\theta$ is the refraction angle given by $\sin \theta = \sin \theta_0 / n_\omega$, where $n_\omega$ is the refraction index [24]. Experimentally, however, we observed that in our samples the photocurrent drops more strongly with increasing $\theta_0$ than expected from Fresnel’s formula. We attribute this effect to a superposition of CPGE with the circular photon drag effect [25] at oblique incidence. Because both effects are proportional to $P_{circ}$ and have the same temparal kinetic, this superposition does not compromise the detector’s functionality.

**DETECTION OF THE ELLIPSE’S AZIMUTH ANGLE WITH BULK GaAs**

To obtain all Stokes parameters besides the CPGE which provides an information on the radiation helicity, an additional detector element for determination of the ellipse azimuth is needed [1]. In our previous work aimed at the detection of THz radiation we used for this purpose the linear photogalvanic effect in SiGe QWs. The LPGE in SiGe structures is also detected in the mid-infrared range [26]. However, the signal is rather small and the response is obtained only at wavelength about 10 $\mu$m under resonant intersubband transitions. To search for other materials, with the aim to increase the sensitivity and to extend the spectral range of the detector, we analyze here the LPGE in bulk GaAs crystals. Bulk GaAs crystals belong to $T_d$ point group symmetry. While the CPGE in materials of this symmetry is forbidden, an LPGE current can be generated applying linearly or elliptically polarized radiation.

We prepared (111)-oriented $p$-type GaAs samples of
yield transverse signals given by the radiation power \( V/P \) in bulk Te (circles) and bulk GaAs (triangles) samples at room temperature. The signals are obtained at \( \lambda = 9.7 \mu m \) applying pulsed TEA CO\(_2\) laser radiation. Full and dashed lines are fits after \( V_{1s}/P \propto \sin 2\phi \) and \( V_{[110]}/P \propto \sin 4\phi \) for Te and GaAs, respectively. Insets show the experimental geometry for both samples. In the GaAs-detector unit the signal of each contact pair is fed into a differential amplifier floating against ground.

\[ C(\omega) \] is a constant factor being proportional to the only one non-zero component of the third rank tensor \( \chi \) [\[24\]]. In our experimental set-up where the radiation ellipticity is varied by the rotation of the quarter-wave plate by an angle \( \phi \), \((E_x^2-E_y^2)/|E|^2 = (1+\cos 4\phi)/2 \) and \((E_x^2+2E_xE_y)/|E|^2 = \sin 4\phi/2 \). Applying infrared radiation we clearly detected both dependences of the photosignal. Figure 4 shows the angle \( \phi \) dependence of \( V_{[110]}/P \) obtained applying radiation at \( \lambda = 9.7 \mu m \).

From the angle \( \phi \) dependence we obtain the LPGE constant \( C(\omega) \) which determines the detector element sensitivity providing the calibration of the device. Figure 3 shows the spectral behaviour of the constant \( C(\omega) \) at infrared wavelengths obtained by the Q-switched CO\(_2\) laser. The sensitivity of the order of 20 mV/kW is measured for the angle \( \phi = 22.5^\circ \) at which signal achieves its maximum value. This value is comparable to that of the HgTe QW CPGE-detector unit. We also obtained a considerable signal in the terahertz range characterized by the same angle \( \phi \) dependences. Here the sensitivity at 148 \( \mu m \) is also comparable to that of the HgTe QW CPGE-detector unit and is about 20 times higher than that measured previously in SiGe QWs [\[2\]].

To obtain the Stokes parameters of a radiation field the signals from HgTe QW and bulk GaAs must be measured simultaneously. In the work on a THz ellipticity detector we simple stacked the CPGE- and the LPGE-detector units. This arrangement is only possible if the first of the two elements is practically transparent to the incident radiation. Therefore we carried out FTIR measurements of the transmission of HgTe QW. These data are shown in insets to Figs. 3 and 2. The essential result is that the sample is almost transparent and can be used in a stacked configuration. The transmittance in the whole spectral range is about 30-40 percents which just corresponds to the reflectivity of the sample. The oscillations in the spectrum are due to interference in the plane-parallel transparent semiconductor slab. The magnitude of the reflection can be reduced by anti-reflection coatings improving the sensitivity of the detector system.

**STOKES PARAMETERS**

From the signals obtained by the CPGE-detector unit (HgTe QW) and by the LPGE-unit (bulk GaAs) it follows that simultaneous measurements of two signals allow one the determination of the Stokes parameters which completely characterize the state of polarization of the radiation field. The Stokes parameters defined according to [\[28\]] are directly measured in our detector units yielding

\[
\begin{align*}
\sigma_0 &= |E|^2, \\
\sigma_1 &= \frac{|E_x|^2 - |E_y|^2}{|E|^2} = \frac{V_{GaAs}^{[110]}}{P \cdot C(\omega)}, \\
\sigma_2 &= \frac{E_xE_y^* + E_yE_x^*}{|E|^2} = \frac{V_{GaAs}^{[112]}}{P \cdot C(\omega)}, \\
\sigma_3 &= \frac{i(E_yE_x^* - E_xE_y^*)}{|E|^2} = \frac{P_{circ}}{P \cdot S(\omega)}.
\end{align*}
\]

where the parameter \( \sigma_0 \propto P \) does not contain information about the polarization state and determines the radiation intensity.

**CPGE UNIT BASED ON BULK Te**

Finally we investigated CPGE in another narrow band semiconductor — bulk Te — with respect to its appli-
cability in an ellipticity detector and compare the results with the data on HgTe QW structures. In fact bulk Te was the first material in which the CPGE was detected [29]. Single crystal Te belongs to the point group $D_3$ where second rank pseudotensors are diagonal in a coordinate system with $z$ along the trigonal crystallographic axis. This axis is also the growth direction of bulk crystals. The macroscopic shape of Te is hexagonal. Thus, irradiating a sample along $z$ direction generates a longitudinal current along this axis. Equation (2) yields for the photosignal $V_z \propto j_z$ in Te [30]

$$V_z/P = \tilde{S}(\omega)P_{\text{circ}}.$$  

(6)

In order to measure this current we prepared two contacts around circumferences of hexagonal prism shaped specimens, see inset in Fig. 5. We used $p$-doped tellurium crystals which at room temperature have the hole concentration of about $3.5 \times 10^{16}$ cm$^{-3}$. The samples were of 11.5 mm long and had a cross section of $\approx 20$ mm$^2$. Illuminating the crystal along $z$ axis by mid-infrared radiation we detected a polarization dependent signal reversing polarity upon switching the radiation helicity (see Fig. 5). In our experimental set-up the radiation helicity is varied by the rotation of the quarter-wave plate by an angle $\varphi$ according to $P_{\text{circ}} = \sin 2\varphi$. The signal $V_z$ is well described by this dependence. The possible contribution of the longitudinal photon drag effect is vanishingly small in our samples at room temperature in agreement to Ref. [29]. Figure 3 shows the spectral behaviour of the sensitivity of the Te sample obtained for circularly polarized radiation. Our investigations demonstrate that in this material the sensitivity in the mid-infrared is about 10$^8$ times higher than that of Te even when applying the highest available radiation power.

Finally we note that a further increase of the sensitivity may be obtained by using multiple QWs and technologically available (112)-grown samples.

We thank S.A. Tarasenko, E.L. Ivchenko and V.V. Bel’kov for useful discussions. The financial support of the DFG and RFBR is gratefully acknowledged. Work of L.E.G. is also supported by “Dynasty” Foundation — ICFPM and President grant for young scientists.

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