Characterization of (Cd,Mn)Te and (Cd,Mg)Te single crystals in the THz frequency range using integrated photoconductive and electro-optic effects

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Abstract. We present THz frequency range characterization of highly resistive (Cd,Mg)Te and (Cd,Mn)Te single crystals, using an “experiment-on-chip” configuration. We have demonstrated that both of these single crystals exhibit simultaneously strong photoconductive (PC) and electro-optic (EO) effects by performing measurements on a given single platelet with a deposited Au coplanar transmission line. We optically generated a subpicosecond electrical transient by focusing an ultraviolet 100-fs-wide pump pulse between the electrodes of a dc-biased coplanar line (PC effect) and, subsequently, time resolved it with a subpicosecond resolution along the transmission line using an internal EO effect by passing infrared, 100-fs-wide probe pulses through the crystal between the coplanar strips. Transients sampled at different distances from the generation site allowed us to calculate the complex propagation factor $\gamma(f)$ of our transmission lines and the corresponding THz bandwidth attenuation and phase velocity. The latter parameters enabled us to reconstruct the original ~600-fs-in-duration, PC-generated transient by “back-propagating” a signal to the excitation point. Furthermore, we have also determined the THz-bandwidth EO coefficients of our (Cd,Mn)Te and (Cd,Mg)Te crystals to be 6 pm/V and 1.2 pm/V, respectively.

1. Introduction
Ternary compounds based on the CdTe crystal structure, such as Cd$_{1-x}$Mg$_x$Te [(Cd,Mg)Te, (CMgT)], Cd$_{1-x}$Zn$_x$Te [(Cd,Zn)Te, (CZT)], and Cd$_{1-x}$Mn$_x$Te [(Cd,Mn)Te, CMnT] have recently been receiving widespread research attention because of their interesting physical properties with broad device applications, ranging from photoconducting and optoelectronic to magneto-optic. The main advantage of ternary compounds over plain CdTe single crystals is that incorporation of the third element leads to an enhancement of their energy bandgap $E_G$ with only minimal deterioration of either crystalline or transport (carrier mobility) parameters. The increase of the value “x” leads to roughly a linear increase of $E_G$, which optimizes the device’s performance. They are also very highly resistive materials, and with additional carrier compensation using, e.g., shallow trap states can reach resistivities above $10^{10}$ Ω-cm. While CZT has become a leading material for solid-state x- and gamma-ray detectors [1], CMnT single crystals are the most-studied diluted magnetic semiconductors [2]. They possess unique
magneto- and electro-optic properties [3,4], and most recently have been successfully implemented in time-resolved x-ray detectors [5]. (Cd,Mg)Te is the most-recent extension of the CdTe-based ternary family [6] and exhibits the widest $E_G(x)$ tuning range, which extends from the near infrared to the visible part of the spectrum.

2. Sample fabrication and experimental setup

Our CMgT and CMnT samples were grown using a vertical Bridgman method, following procedures described in [7] and [8], respectively. After the growth, the crystals were cut into ~50-mm$^2$-area, 1-mm-thick platelets. CMnT crystals were also annealed in Cd vapour to improve their crystallinity and reduce the number of Cd vacancies, while CMgT crystals were Ge doped. In both cases, their resulting resistivities were at least at the $10^5 \Omega \cdot \text{cm}$ level. A 200-nm-thick Au film was sputtered on the top (110) surface of the samples; subsequently, coplanar strip (CPS) transmission lines were fabricated using optical lithography and a lift-off process. Fabricated CPS lines were 100-µm wide with a 25-µm gap, as shown in the inset in figure 1.

Time-resolved measurements of the photoconductive (PC) response using the electro-optic (EO) sampling technique were performed using an “experiment-on-chip” configuration described in detail in [9]. Briefly, we used a mode-locked Ti:sapphire laser emitting a train of ~100-fs pulses at 830 nm at a 76-MHz repetition. The output was split, using a 60/40 beam splitter, into a sampling beam and an excitation beam, the latter of which was frequency doubled using a BaB$_2$O$_4$ crystal. The excitation pulses (blue light, 415 nm) were focused to an ~50-µm-diam spot to uniformly illuminate the gap between the dc-biased CPS lines, forming a so-called PC sliding contact [10] (see the inset in figure 1), and triggering surface-photo–generated electrical transients, which were launched into the CPS line. The sampling pulses (infrared light, 830 nm) were focused to a 25-µm-diam spot and passed through the gap between the CPS lines. In the presence of an electric field from a propagating electrical transient, their polarization plane was tilted by $\delta$ degrees because of the Pockels (EO) effect, which for the F-43m symmetry group can be expressed as [11]

$$\delta = \frac{2\pi n^3(\lambda) r_{41} V L}{\lambda d},$$

where $n(\lambda)$ is the refractive index at the wavelength $\lambda$ of the probe beam, $V$ is the applied voltage, $d$ is the CPS electrode separation distance, $r_{41}$ is the EO coefficient, and $L$ is the interaction length, i.e., penetration of the electric field into the crystal. On the other side of the sample, the probe beam was fed into a polarizing beam splitter and, finally, detected by a pair of balanced photodetectors and a lock-in amplifier at the modulation frequency of the pump pulse train.

The system response was calibrated by measuring the voltage response (amount of birefringence) induced by a continuous-wave sinusoidal signal with a 1.16-V amplitude and a 243-kHz frequency applied between the CPS lines under a standard assumption that the EO effect is not sensitive to the electric-field frequency so long as the energy of the probing photons is below $E_G$ of an EO crystal [10].

Figure 1: Time-resolved PC response of a CMnT crystal with the inset featuring our “experiment-on-chip” configuration, with excitation and sampling beams, blue and red dots, respectively. The excitation pulse had a pump power of 10 mW with a 415-nm wavelength. A 10-V dc bias was applied to the CPS lines.
3. Experimental results and discussion

We collected a number of CMgT and CMnT photoresponse transients at several distances away from the excitation point, ranging from 100 to 300 µm. Figure 1 features a transient recorded 150 µm from the excitation point for CMnT. The signal exhibits a 3.5- ps rise time (based on the 10% to 90% amplitude criterion), while its trailing edge represents the photocarrier relaxation dynamics and can be very well fitted by a single exponential function with a decay time of 3.7 ps. A slightly wider transient was recorded for the CMgT crystal (not shown).

To determine the dielectric properties of both of our crystals at THz frequencies and the amount of distortion introduced by our CPS line, we performed a standard frequency-domain analysis of our propagated transients [9] and computed frequency-dependent complex propagation factor \( \gamma(f) \) for our transmission lines by dividing the frequency spectra of the waveforms measured at points 150 µm and 250 µm from the excitation spot. Figure 2a presents spectral dependencies of the attenuation constant \( \alpha(f) \) [real part of \( \gamma(f) \)] and the transient phase velocity \( v(f) \) for CMnT (solid lines) and CMgT (dashed lines), respectively. We note that in both cases \( \alpha(f) \) has a rather low value (~4 mm\(^{-1}\) and ~6 mm\(^{-1}\), respectively) and remains constant for up to ~0.6 THz for CMnT and ~0.8 THz for CMgT. At highest frequencies, \( \alpha(f) \) increases very rapidly because of the expected strong increase in the radiative loss of the CPS line [12]. The phase velocity remains essentially flat with an average \( v(f) \) value close to \( 1.3 \times 10^8 \) m/s, so we can conclude that our CPS lines can be regarded as the quasi-TEM (transverse electromagnetic) type.

![Figure 2: (a) Spectral dependencies of the attenuation constant \( \alpha(f) \) and the transient phase velocity for CMnT (solid lines) and CMgT (dashed lines). (b) The intrinsic PC transient of a CMnT crystal acquired by back-propagating the transient sampled at 150 µm from the photoswitch. The inset shows the power spectrum of the intrinsic pulse.](image)

Knowing \( \gamma(f) \), we numerically back-propagated one of the experimental transients toward its zero-distance plane (excitation spot) on the CPS line. The calculated intrinsic transient at the photodetector point for CMnT is shown in figure 2b. We see that it has a peak amplitude of 870 mV, a full width at half maximum (FWHM) of 570 fs, and a fall time of ~700 fs. Note that our intrinsic photoresponse signal has a 3-dB bandwidth up to 560 GHz and a 10% bandwidth above 1.4 THz (figure 2b inset). The signal’s subpicosecond fall time indicates that our CMnT crystal must have a large number of shallow traps, and that trapping is the main early-stage carrier relaxation mechanism. Not shown are similar results for the CMgT crystal: an intrinsic pulse had an amplitude of 750 mV, a FWHM of 620 fs, and 3-dB and 10% bandwidths ~ 480 GHz and above 1.2 THz, respectively.

In our experiment-on-chip configuration, the crystals themselves act as EO intensity modulators and measure the change in probe intensity that, subsequently, is recorded by the photodetector and read out by the lock-in as the voltage \( \Delta V \). Using the differential transfer function of our EO sampling system [9], we can determine the optically induced phase retardance \( \delta \) and calculate \( r_{41} \) from Eq. 1. As a reference point, we used an averaged pump power of 10 mW. Under these conditions, \( \Delta V = 150 \)
\( \mu \text{V} \) and 30 \( \mu \text{V} \) for CMnT and CMgT, respectively, at a distance of 150 \( \mu \text{V} \) from the photoswitch. Ellipsometry measurements were performed and determined that \( n(\lambda = 830 \text{ nm}) = 3.0 \) for both samples. The field interaction length \( L \) in Eq. 1 was taken as the inverse of \( \alpha(f) \) for moderate frequencies (see figure 2a). Using the above values, as well as the peak amplitudes of our electrical transients (figure 1) and the CPS dimensions, we calculated \( r_{41} \) to be \(-6\) and \(-1.2 \text{ pm/V} \) for CMnT and CMgT, respectively, well within the range of EO coefficients reported in the literature [14].

4. Conclusions
We have demonstrated simultaneous subpicosecond PC and EO effects, measured in the same CMgT and CMnT single-crystal samples with a separation distance between PC excitation and EO sampling as short as 150 \( \mu \text{m} \). By sampling the PC transients at different points along the transmission line, we managed to fully characterize propagation of our signals along the CPS line at the sub-THz frequency range, specifically the phase velocity and the attenuation constant. By back-propagating our experimental waveforms, we obtained the intrinsic PC transients, generated using 100-fs-wide, 415-nm-wavelength optical pulses. For CMnT, e.g., such transient exhibited for a 570-fs pulse width with an amplitude of over 700 mV. The observed subpicosecond PC response demonstrates that these crystals should function well as ultrafast radiation detectors. Finally, we were able to calculate THz-frequency \( r_{41} \) coefficients for both of our CMnT and CMgT crystals.

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