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Femtosecond electro-optic effect in (Cd,Mn)Te single crystals

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Abstract. We present our studies on the femtosecond electro-optic (EO) effect in high quality $\text{Cd}_{0.88}\text{Mn}_{0.12}\text{Te}$ (CMT) single crystals, grown using a modified vertical Bridgman method. Our time-resolved experiments were performed using a coplanar transmission line setup, which incorporated a free-standing, low-temperature-grown GaAs photoconductive switch as a sub-picosecond electrical pulse generator and the tested CMT crystal as an active EO transducer. We determined the r -coefficient (r_{41}) of CMT at the high (THz) frequency range to be 29.4 pm/V, an order of magnitude greater than that measured for the same sample at low (MHz) frequencies. The observed suppression of the EO coefficient at low frequencies was due to effective electric field screening by free holes in the crystal volume. Comparison to the standard EO sampling scheme based on the LiTaO_3 transducer showed that CMT exhibited the same sub-picosecond temporal resolution with significantly greater voltage sensitivity. We also did not observe, the so-called dielectric loading typical for LiTaO_3 -based samplers.

1. Introduction

The (Cd,Mn)Te system is among the most-studied, II-VI, diluted-magnetic semiconductors, due to its strong magnetic properties and the stable zinc-blend structure for Mn concentrations up to 0.70, resulting in the very wide energy band gap tuning range. Applications of the (Cd,Mn)Te compound vary from spintronics and Faraday isolators to x- and γ -ray detectors [1].

An electro-optic sampling (EOS) technique is a powerful tool allowing a minimally invasive means of characterizing performance of ultra-high-speed (THz bandwidth) electronic and optoelectronic devices, such as novel transistors, diodes, photodetectors, and transmission lines by exploiting the linear EO Pockels effect [2]. The EOS system enables one to precisely resolve sub-picosecond nonlinear transient effects and characterize ultrafast electrical pulses [3].

We present here EO experiments demonstrating that our $\text{Cd}_{0.88}\text{Mn}_{0.12}\text{Te}$ (CMT) single crystal is an excellent substitute for the commonly used LiTaO_3 , and showing that the CMT EO-coefficient r_{41} at THz frequencies (THz-f) is much greater than the low-frequency (low-f) values reported by Yariv [4] and Chen [5].

2. Configuration of EOS experiment and fabrication details

Our EOS system was realized using a 76-MHz repetition rate Ti:Sapphire laser providing 100-fs-wide pulses with an 800-nm wavelength. The laser beam was split by a 70/30 beam splitter into two beams:

the excitation (pump) beam and sampling (probe) beam. The pump beam, modulated at 256 kHz by an acousto-optic (AO) modulator, illuminated our device under test (DUT), namely, a free-standing photoconductive switch incorporated into a coplanar strip (CS) transmission line [3]. The switches were produced from low-temperature grown (200–300 °C) GaAs (LT-GaAs) rapidly post-annealed at 600 °C. The 25x25 μm^2 LT-GaAs chips, removed from the native substrate, were placed into pre-etched 500-nm-deep wells in the MgO substrate [6]. Next, a Ti/Au CS line was deposited above the switch sides, securing it between 20- μm -wide signal and ground lines, separated by a 20- μm gap.

The sampling beam, on the other hand, traversed a computer controlled delay line, half-wave plate, polarizer, and was ultimately focused by a microscope objective upon our CMT EO transducer placed above the CS line near the DUT. The CMT crystals used in this study were fabricated using a modified vertical Bridgman method, in which a seed crystal of CdTe was placed at the bottom of a growth ampoule beneath a melt of Cd, Te and Mn. The ampoule was then slowly lowered from the furnace allowing the solution to crystallize into a zinc-blend structure. As-grown CMT is inherently *p*-type due to Cd vacancies and can have conductivity as high as 0.1 S/cm [7]. The crystals for EO transducers were cut along the (110) face to provide the greatest Pockels effect.

In the presence of an electrical field transient, the EO transducer acts as an optical intensity modulator for the transmitted sampling beam pulses with the output directed to a polarizing beam splitter and two photodetectors connected to a lock-in amplifier synchronized to the AO modulation frequency of the excitation beam. The orientation of the transducer was such that the EO-axis was aligned parallel to the electric field, and 45° with respect to the probe beam polarization.

3. Electro-optic measurements and analysis

Figure 1 presents an ultrafast EOS measurement taken using the $\text{Cd}_{0.88}\text{Mn}_{0.12}\text{Te}$ crystal as an EO transducer. We observe a very clean pulse with the full-width-at-half-maximum (FWHM) of ~1 ps and excellent signal-to-noise ratio. Since the free-standing LT-GaAs switch used in our experiments as the DUT is well-known for generating electrical transients as short as 360 fs [3], our CMT transducer faithfully recorded the photoswitch signal, which dispersed somewhat due to approximately 250- μm propagation distance between the switch position on the CS line and the sampling spot on the CMT crystal.

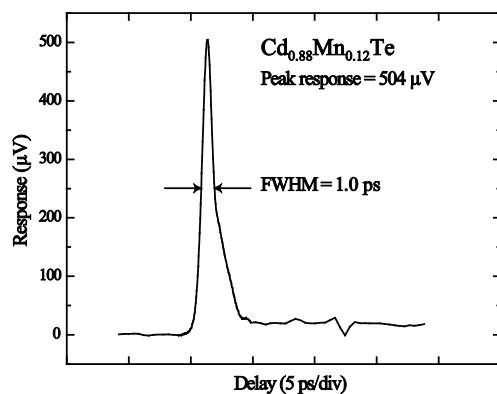


Fig. 1. Ultrafast EOS response with CMT transducer. The LT-GaAs switch operated under 4-mW pump illumination and 20-V bias.

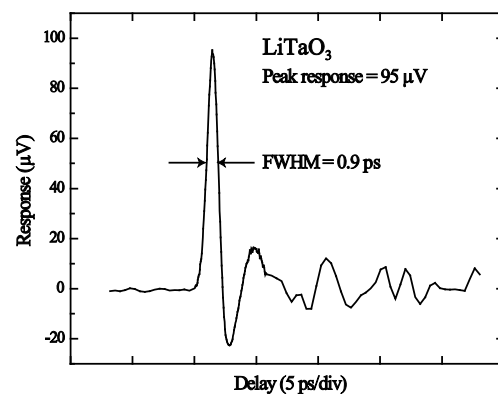


Fig. 2. Ultrafast EOS response with LiTaO_3 transducer. The LT-GaAs switch operated under 4-mW pump illumination and 20-V bias.

For comparison purposes, we repeated the same experiment with the standard LiTaO_3 EO transducer rather than the CMT crystal. Figure 2 shows the recorded electrical transient. As expected, the FWHM of the measured pulses are approximately the same. The post-pulse oscillations are characteristic for LiTaO_3 sensors and reflect the so-called dielectric loading due to the large dielectric mismatch between the LiTaO_3 crystal and the CS line fabricated on MgO. What is surprising is that under the

same experimental conditions (the same signal generated by the DUT), the pulse recorded by CMT had roughly five times greater response amplitude over the LiTaO₃ result. Literature, however, indicates that CMT has a relatively small Pockels effect ($r_{41} \sim 4.5$ pm/V) [4], resulting in a calculated EOS response smaller than that from a LiTaO₃ crystal, clearly conflicting with our measurements.

The EO measurement reflects the optical retardation Γ of the polarized probe beam. The EOS system directly measures the change in probe light intensity (ΔV , as measured by the photodetectors) at each position along the optical delay path, for which the differential transfer function is given by:

$$\frac{\Delta V}{V_0} = \frac{1}{2} \sin(\pi V / V_\pi) \approx \frac{\pi V}{2V_\pi}, \quad (1)$$

where V is the absolute measurement of the signal pulse, V_0 is the DC component (31.5 mV/ μ W times the probe light power), and V_π is defined as the voltage required retarding the polarized probe by π . The retardations for LiTaO₃ and CMT under the current configuration are, respectively, given by:

$$\Gamma_{LTO} = \frac{2\pi(n_e - n_o)L_1}{\lambda} - \frac{\pi(n_e^3 r_{33} - n_o^3 r_{13})L_2}{\lambda d} V, \text{ and} \quad (2)$$

$$\Gamma_{CMT} = \frac{\sqrt{2}\pi(n_o^3 r_{41})L_2}{\lambda d} V, \quad (3)$$

where n_e and n_o are the extra-ordinary and ordinary refractive indices, λ is the probe wavelength, d is the gap between transmission lines, the crystal thickness is L_1 , and the interaction length between crystal and electric field is L_2 . For the non-isotropic x -cut LiTaO₃ there are two significant EO coefficients, r_{33} and r_{13} , while for the isotropic CMT, the only nonzero EO-coefficients are $r_{41} = r_{52} = r_{63}$. It is important to note that the first term in (2) is the intrinsic (static) birefringence of LiTaO₃, and in our experiments was compensated by a second LiTaO₃ crystal of identical thickness with crystal orientation perpendicular to the first one.

A significant factor in calculating the absolute value of the EO response is the coupling between the transmission line and EO crystal. In the case of LiTaO₃, the calibration factor V_C is typically obtained by measuring ΔV at low frequencies by applying a voltage sine wave of known amplitude directly to the transmission line, bypassing the photoconductive switch. Knowing r_{33} and r_{13} [4] and the V_C for the LiTaO₃ crystal, we can extract $L_2 = 1.18 \pm 0.26$ μ m from our experimental data using (1) and (2). The low value of L_2 is further corroborated by the estimated air gap of 24 μ m between the CS line and the crystal. The air gap was calculated by the impedance of coplanar strip lines within multilayer substrates [8] using the effective dielectric ($\epsilon_{\text{eff}} = c^2/v^2$), where c is the speed of light, and v is the velocity of the pulse. Assuming the same air gap, the CS characteristic impedance and ϵ_{eff} were, subsequently, calculated for the CMT transducer, as well as its corresponding V_C value.

Plugging the above parameters into (1) and (3) and knowing that for Cd_{0.88}Mn_{0.12}Te $n_o = 2.94$ for $\lambda = 800$ nm [9], we calculated the low-f r_{41} to be 2.8 ± 0.8 pm/V. The obtained value is in close approximation to the CdTe r_{41} value of 4.5 pm/V presented by Yariv [4] and the Cd_{0.75}Mn_{0.25}Te value ($r_{41} = 3.5 \pm 0.2$ pm/V) calculated in [5], but is much too small to account for the very large signal presented in figure 1. Therefore, we need to use the data obtained directly from our ultrafast EO experiment (figure 1) as the calculation starting point. In such situation, we find that the THz-f measurement of r_{41} is 29.4 ± 6.1 pm/V, an order of magnitude greater than the earlier calculated value at low-f (MHz). Under the optimal configuration (incident polarization parallel to electric field [4]) V_π is as low as $556 \pm 106 \cdot d/L_2$ V for Cd_{0.88}Mn_{0.12}Te, significantly smaller than that for LiTaO₃ ($V_\pi = 3490 \cdot d/L_2$ V) and ZnTe ($V_\pi = 2911 \cdot d/L_2$ V) [10], the latter being the most often used crystal for free-space THz EO sensing.

To explain the discrepancy between the THz and MHz measurements we propose that free carriers present within our *p*-type crystal effectively screen the low-f voltage signal. The free-carrier screening frequency can be estimated by dividing the CMT crystal's conductivity σ by its permittivity. For as-grown CMT, σ is on the order of 0.1 S/cm [6], providing a free-carrier screening at 125 GHz. Thus, THz-bandwidth transients are much faster than the carrier screening process and CMT is capable of fully rendering the electric field transient, based on the EO effect. These results were corroborated by our low-temperature EO measurements performed on $\text{Cd}_{0.91}\text{Mn}_{0.09}\text{Te}$. At 10 K, the low-f EO coupling was measured to be ten times greater than at 300 K. This indicates that the free carriers suppressing the Pockels effect at room temperature were actually quashed by deep level traps as the temperature lowered. Thermally stimulated discharge current measurements [11] are planned in order to determine the significance and distribution of traps in our CMT crystals.

4. Conclusions

We have shown CMT to be an excellent EO transducer to replace the commonly used LiTaO_3 EO crystal. It is also very promising for free-space THz sensing. The calibration method used here allowed us to obtain the absolute value of r_{41} for CMT and we found that at THz-f it is much greater than that reported for CdTe or ZnTe, and an order of magnitude greater than the measured low-f r_{41} . Substantial carrier screening present in our *p*-type samples was indentified as the cause for the discrepancy between the THz and MHz EO measurements. CMT has a very small V_π , exhibiting a much greater sensitivity over LiTaO_3 in a standard EO sampling set-up. Furthermore, due to its low dielectric constant, a smaller percentage of the signal is lost to reflections along the transmission line and the response signal is much cleaner due to the absence of dielectric loading.

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