

Selection of Silicon Carbide for Electro-optic Measurements of Short Electron Bunches

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Short electron bunch lengths necessitate a new technique of measurement based on cross-correlation of the coherent Terahertz and incoherent visible/UV radiation produced by the electron bunch. Because this technique requires optimal electro-optic properties, an appropriate material must be chosen. 6H Silicon Carbide (SiC) is unsuited due to unfavorable properties in its absorption. After comparing the electro-optic response functions of similar materials and their overall electro-optic performances at optimal optical wavelengths, 3C SiC proves best suited for the measurement process.

I. Introduction

Previously implemented techniques for determining the length of electron bunches are not as well suited for the shorter bunches required for dense collisions at particle accelerators or x-ray region free electron lasers. Older techniques are not only less accurate for shorter bunches but also require averaging over many bunches. This has the disadvantage of lacking information on singular bunches and the changes that occur in these bunches over time.

A more sophisticated technique involves exploiting the relation between types of radiation produced by the electron bunch during synchrotron turns (radiation from centripetal acceleration) or transitions across a conducting screen (shedding of the difference in energy of the two dielectric media). There are then two types of radiation to be concerned with. Coherent radiation occurs in the Terahertz region because the wavelength of this type of radiation is long compared to the length of the bunch. Radiation short compared to the bunch length results in incoherent radiation, in the infrared and above.

Cross-correlation of these types of radiation in an electro-optic crystal allows for measurement of the length of the contributing electron bunch. Figure 1 shows the set-up of an experiment for this measurement. The first stage is splitting the electron bunch's radiation into incoherent and coherent beams. The coherent Terahertz radiation acts as a DC source across the crystal, triggering its electro-optic response. Meanwhile, coherent visible light has become polarized. With the polarization rotation of the electro-optic crystal, light can pass through the

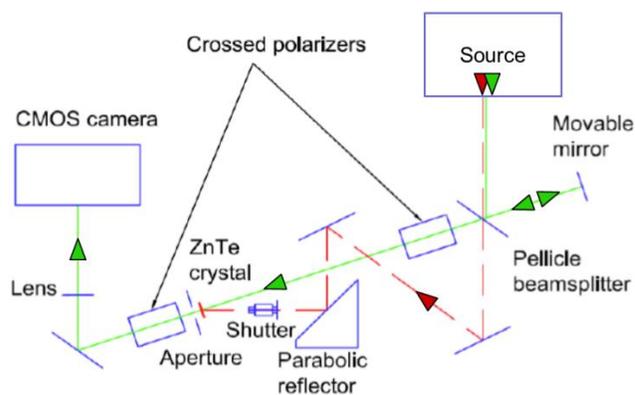


FIG. 1. Experimental set-up demonstrating the measurement of short electron bunches through cross-correlation of coherent THz (red, dashed line) and incoherent visible radiation (green, solid line). Both types of radiation meet at the electro-optic crystal (here, ZnTe) where the THz radiation acts on the crystal and rotates the polarization angle of the visible/UV radiation. From here, the visible comes through at varying intensities to be picked up at the detector.

crossed polarizers and be measured by the visible camera.

This experiment has already been performed using Zinc Telluride (ZnTe) [1]. Results proved the general theory but were relatively weak and provided an estimate of bunch length longer than expected. This behavior was attributed to the selection of ZnTe as the electro-optic material. The new, proposed material for similar measurements was Silicon Carbide (SiC), necessitating an evaluation of the material.

An important choice in the selection of SiC is which polytype to use, 6-Hexagonal or 3-Cubic. Experimental analysis deselected 6H as an option due to complications in its absorption coefficient.

Comparative, numerical analysis of 3C showed it to out-perform similar electro-optic materials. Results support that 3C Silicon Carbide would function well as the electro-optic medium required for short electron bunch measurements.

II. 6H SiC: Experimental Testing

6H SiC has the advantage of being much more affordable than 3C because it is commercially grown and does not require complicated deposition methods. However, because of the targeted market of commercial enterprises, 6H runs the risk of being doped or containing free carriers. While this is useful for applications in which SiC is used as a semiconductor, doping in an electro-optic crystal could cause the material to behave as a metal and block transmission of the visible radiation necessary for measurements of bunch length. Another requirement of using 6H is calculating the angle which maximizes its electro-optic coefficient because normal incidence will not suffice due to the material's hexagonal, low-symmetry structure [2]. To find this angle, 6H's refractive ellipsoid would then need to be derived.

The first concern can be mitigated or alleviated by measuring the transmission of a sample of 6H SiC. Using the BOMEM DA3-002 FTS (Fourier Transform Spectrometer) on a sample 240 microns thick, we measured the angular dependence of 6H's transmission. We observed the expected transmission of pure 6H with increase of transmission towards the Brewster angle. However, while transmission revealed that our sample was not doped as we had worried it might have been, the transmission at each angle revealed an unexpected feature: a drop in transmission at approximately 100 cm^{-1} .

To more quantitatively observe the severity of this drop in transmission, the absorption coefficient of the material is plotted. We derive a function for the absorption coefficient using the relation between transmission and the absorption coefficient:

$$T = (1 - R)^2 e^{-\alpha l}, \quad (1)$$

where T is transmission, R is the reflection coefficient, α is the absorption coefficient, and l is the thickness of the sample [3]. Next we calculate the reflection coefficient from the Fresnel equations at normal incidence [4]. After some minor algebra on Equation 1, we find the frequency dependence of α as:

$$\alpha = \frac{\ln(T) - 2 \ln(1-R)}{-l}. \quad (2)$$

A plot of 6H's absorption coefficient as defined in Equation 2 is provided in Figure 2. Its prime feature provides an absorption coefficient twice as high than those of surrounding frequencies, which even of themselves are non-constant and differ on position in the spectra. While this feature may be the result of optical fold-back or defects in the material, its existence makes 6H unsuited for the precise measurement of bunch length.

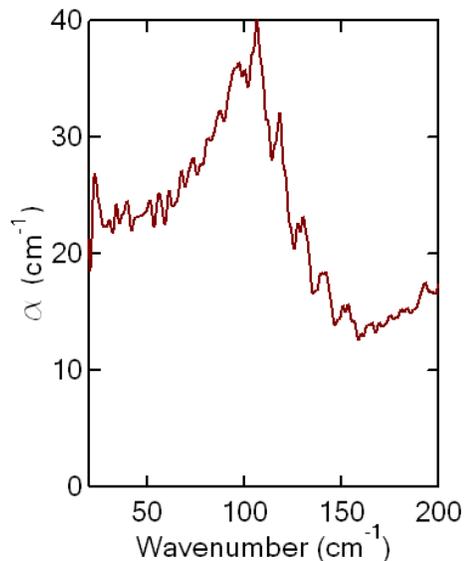


FIG. 2. Absorption coefficient as a function of frequency. The ideal material would be zero at all frequencies, and a more realistic material would have a low, constant value. 6H displays a spike around 110 cm^{-1} in addition to a changing background absorption.

III. 3C SiC: Numerical Calculations

With 6H SiC unqualified for its proposed use, we are left with 3C SiC which gives some benefits. Namely, 3C does not require the same effort to maximize its electro-optic coefficient by angle. As a zinc-blende structure similar to Zinc Telluride (ZnTe) and Gallium Phosphide (GaP), comparing its electro-optic response to similar materials is also possible.

The electro-optic response gives the range of useful frequencies that can be measured in a material, limited by the material's transverse optical (TO) resonance. ZnTe displays TO resonance at 5.3 THz, GaP at 11 THz [2], and SiC at 23.8 THz [5]. This material-dependent range of useful frequencies is defined in the material's electro-optic response function. For electro-optic response, the following equation was used:

$$G(f, d) = \frac{2}{1+n(f)+i\kappa(f)} \frac{1}{d} \text{Abs} \left[\int_0^d \text{Cos} \left(2\pi f z \left(\frac{1}{v_{ph}(f)} - \frac{1}{v_g} \right) \right) dz + i \int_0^d \text{Sin} \left(2\pi f z \left(\frac{1}{v_{ph}(f)} - \frac{1}{v_g} \right) \right) dz \right], \quad (3)$$

where G is the electro-optic response, f is frequency, d is crystal thickness, $n(f)$ and $\kappa(f)$ are the real and imaginary parts of the refractive index, v_{ph} is phase velocity at the THz frequency, and v_g is group velocity at the optical frequency [2]. The functions $n(f)$ and $\kappa(f)$ are defined by the following relations between the real and imaginary parts of the dielectric function, respectively:

$$\epsilon_r = n^2 - \kappa^2, \text{ and} \quad (4)$$

$$\epsilon_i = 2n\kappa. \quad (5)$$

It is the mismatch between the THz phase velocity and the optical group velocity that determine the electro-optic response. Casalbuoni calculates optical group velocity using dispersion models for ZnTe and GaP that are not adequately available for SiC. Phase velocity, on the other hand, is calculated using a damped oscillator model [2].

Because we lack a dispersion curve for SiC, a dielectric model that presents the dispersion in the visible/UV regions must be constructed. To do this, a model of the real dielectric function was constructed which depicted resonances as Lorentz oscillators in the following form:

$$\epsilon_r(\omega) = \epsilon_\infty + \frac{S_{ir}}{\omega_{ir}^2 - \omega^2 - i\Gamma_{ir}\omega} + \frac{S_{uv}}{\omega_{uv}^2 - \omega^2 - i\Gamma_{uv}\omega}, \quad (6)$$

where ω is the wavenumber, ϵ_∞ is the high frequency dielectric constant, S_{ir} is the strength and Γ_{ir} the damping coefficient of the resonance located at ω_{ir} , and S_{uv} is the strength and Γ_{uv} the damping coefficient of the resonance located at ω_{uv} . For our simple, visible model we neglect damping. The resonances of this model were found [6] and their strengths assigned by fitting SiC's dielectric constants and previously published data in the visible and UV regions [6, 5]. The parameters of the fit for the simple, visible model are provided for SiC in Table 1.

Table 1. Parameters for dual oscillator dielectric model

ϵ_∞	ω_{ir}	S_{ir}	ω_{uv}	S_{uv}
6.52	794 cm^{-1}	$1.47 \times 10^6 \text{ cm}^{-2}$	54072 cm^{-1}	$3.02 \times 10^9 \text{ cm}^{-2}$

For the THz frequencies, a simple model of the dielectric function neglecting imaginary components and width of the resonance would not suffice. SiC's THz model must match the damped oscillator model

provided for ZnTe and GaP [2] of the form presented in Equation 6, this time including only the IR resonance augmented by the resonance's damping. The parameters of the THZ model for 3C SiC are shown in Table 2.

Table 2. Parameters for damped oscillator dielectric model

ϵ_∞	ω_{ir}	S_{ir}	Γ_{ir}
6.7	794.5 cm^{-1}	$2.15 \times 10^6 \text{ cm}^{-2}$	8.51 cm^{-1}

To compare each material at its optimal performance, the optical frequency that provided the closest match-up between the optical group velocity and the THz phase velocity was calculated. ZnTe was calculated to match best at 12500 cm^{-1} and GaP matched at 8352 cm^{-1} from visible/IR models [2]. For SiC, match-up occurred at the optical frequency 37495 cm^{-1} . It should be noted that this frequency (in the mid-UV) occurs at a lower, more easily accessible frequency in actuality because of peak width associated with the UV resonance that could not be included in the model used for this project.

Having optimized the optical frequency specific to each material, a comparison is attempted between the three. Figure 3 illustrates one such comparison where the frequency cut-off for each crystal is the same.

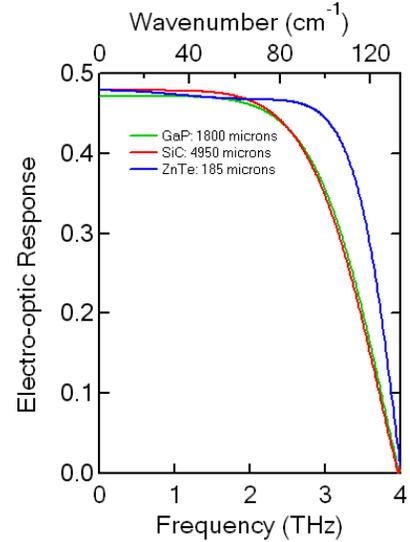


FIG. 3. Presentation of the electro-optic responses at the same cut-off of ZnTe, GaP, and SiC with thicknesses 185 microns, 1800 microns, and 4950 microns, respectively. Electro-optic coefficient multiplied by thickness (given in $10^{-12} \text{ m/V} \times \text{microns}$) is presented as a figure of merit: ZnTe-740, GaP-900, SiC-13365.

The parameter varied to reflect this frequency range is thickness. For ZnTe, the 4 THz band almost reflects the upper range of accessible frequencies at any thickness due to its low TO resonance. GaP must be

made significantly thicker and SiC even more so to fall to a similar frequency range. This comparison proves incomplete in regards to total electro-optic performance because it does not reflect the full range capabilities of GaP or SiC and also neglects the importance of the electro-optic coefficient. As a figure of merit, the electro-optic coefficients (in $10^{-12} m/V$: ZnTe-4, GaP-0.5, and SiC-2.7) [2, 9] times the crystal thickness represents the material's rotation of the polarization in the presence of a THz field. At the limited range, ZnTe and GaP display similar figures of merit, but SiC exhibits a figure of merit two orders of magnitude higher.

The comparison of each material's figure of merit at identical frequency ranges helps to give a more complete picture of the crystals. However, it fails to adequately convey SiC's broad band capabilities in the THz region. To remedy this, another comparison is shown in Figure 4. This comparison focuses on the possible frequency ranges of the crystals' response functions while holding each to the same performance relating to the rotation of the polarization, expressed in the figure of merit being fixed at 500. From this type of comparison, one can easily note the broader range of SiC against ZnTe's range, limited from TO resonance, and GaP's, limited by the crystal thickness required to keep its figure of merit as high as its counterparts with stronger electro-optic coefficients.

IV. Conclusions

Due to the material issues leading to unfavorable absorption features, 6H SiC provides a poor choice for the electro-optic crystal necessary for short bunch length measurement. The benefits of 3C include broad-band capabilities in the electro-optic response of the THz region not present in similar materials and a fair electro-optic coefficient useful for polarization rotation. Optimal or close to optimal optical frequencies (visible/UV, not IR) greatly benefit the performance of SiC. Silicon Carbide's material properties suggest it should be tested as the electro-optic medium required for electron bunch measurements which utilize cross-correlation of coherent and incoherent radiation.

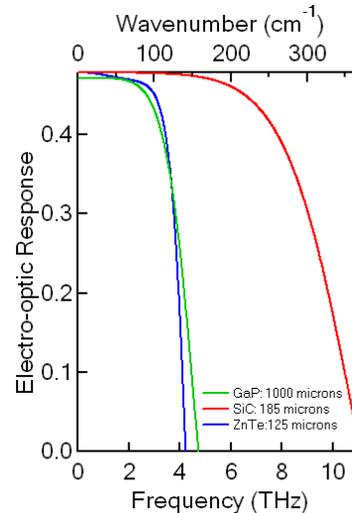


FIG. 4. Display of electro-optic responses of zinc-blende crystals held at the same figure of merit, 500. While ZnTe benefits little from its decreased thickness due to the nearness of its resonance, GaP responds poorly due to its compensation of low electro-optic coefficient with greater thickness. SiC, at moderate thickness, shows a much greater useful frequency band than either of the other materials.

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