Investigation of Laser-Induced Currents in Large-Band-Gap Dielectrics

Sabine Keiber[1,2,*], Tim Paasch-Colberg[1], Alexander Schwarz[1,2], Olga Razskazovskaya[1], Elena Fedulova[1], Özge Sağlam[3], Clemens Jakubeit[1], Shawn Sederberg[1], Péter Dombi[1], Nicholas Karpowicz[1], and Ferenc Krausz[1,2]

[1]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany, [2]Fakultät für Physik, Ludwig-Maximilians-Universität, Am Coulombwall 1, D-85748 Garching, Germany ,[3] Physik-Department, Technische Universitat München, James-Franck-Strasse, D-85748 Garching, Germany

** Author e-mail address: sabine.keiber@mpq.mpg.de*

Abstract: Applying few-cycle laser pulses to dielectrics increases their ac-polarizability, allowing for switching currents at the frequency of light [1]. We report on the dependence of these ultrafast currents on material band gap and sample geometry.

1. Introduction

Recent experiments investigating electron dynamics on the ultrashort timescale in solids have shown exciting results from the generation of high harmonics [2] to the observation of Bloch oscillations [3]. These experiments have only recently become possible due to the advancement of ultrafast laser sources, which allow material properties to be probed at field strengths of a few V/Å, far above the dc damage threshold.

The detection of ultrafast currents which are sensitive to the carrier envelope phase (CEP) of the applied laser pulses has opened the door to new metrology techniques [4] and is a first step towards PHz optoelectronics [1]. This work aims at getting a better understanding of the nature of the detected current and its dependence on material properties as well as sample geometry.

2. Experimental Setup and Results

Visible/near infrared laser pulses with 400 µJ energy are generated at a repetition rate of 3 kHz by a customized Ti:Sapphire chirped-pulse amplifier system. The pulse duration of the CEP-stable pulses is 4 fs (FHWM), corresponding to about 1.5 optical cycles at the carrier wavelength of 760 nm. The linearly polarized beam is focused with an off-axis-parabolic mirror to a diameter of about 60 µm ($1/e^2$) onto the sample which consists of a 250 µm thick dielectric substrate coated with a 200 nm silver layer on both sides (see Fig. 1). The current between the electrodes is amplified and filtered from the CEP-independent background using a lock-in amplifier. No bias voltage is applied to the electrodes.

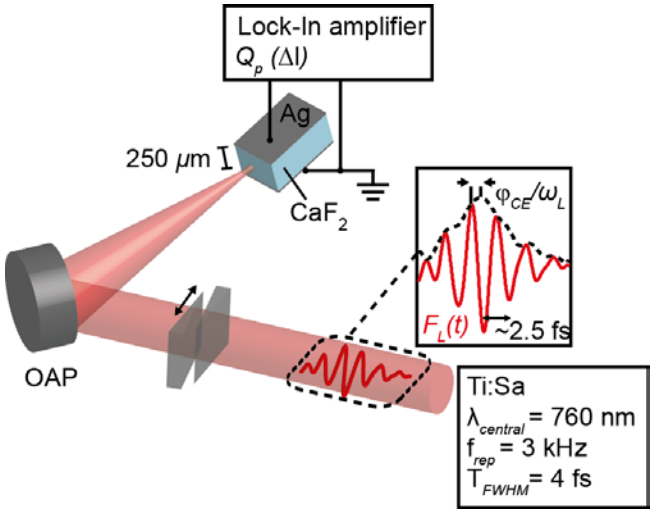

Fig. 1. Experimental Setup, adapted from [4]. The edge of a 250 µm thick dielectric substrate is illuminated by few-cycle Ti.Sapphire pulses at a repetition rate of 3 kHz. The beam is polarized perpendicularly to the gap formed by two silver electrodes and focused down to about 60 µm ($1/e^2$), providing electric field strengths of a few V/Å. The CEP-dependent transferred charge is measured with a lock-in amplifier.

When changing the CEP of the applied laser pulse by scanning a pair of fused silica wedges, we record oscillations in the transferred charge per pulse (see Fig. 2 a). The amplitude of the charge oscillation varies depending on the dielectric material used in the measurement. For investigating how the transferred charge depends on band gap (E_g), three crystalline dielectrics with the space group $Fm\bar{3}m$ were chosen: CaF_2 (E_g = 12.1 eV), BaF_2 (E_g = 9.1 eV) and MgO (E_g = 7.8 eV). As can be seen in Fig. 2 b), the critical field strength, at which the signal sets in, increases with band gap. The signal decrease in MgO around 1.5 V/Å coincides with the onset of ablation of the material.

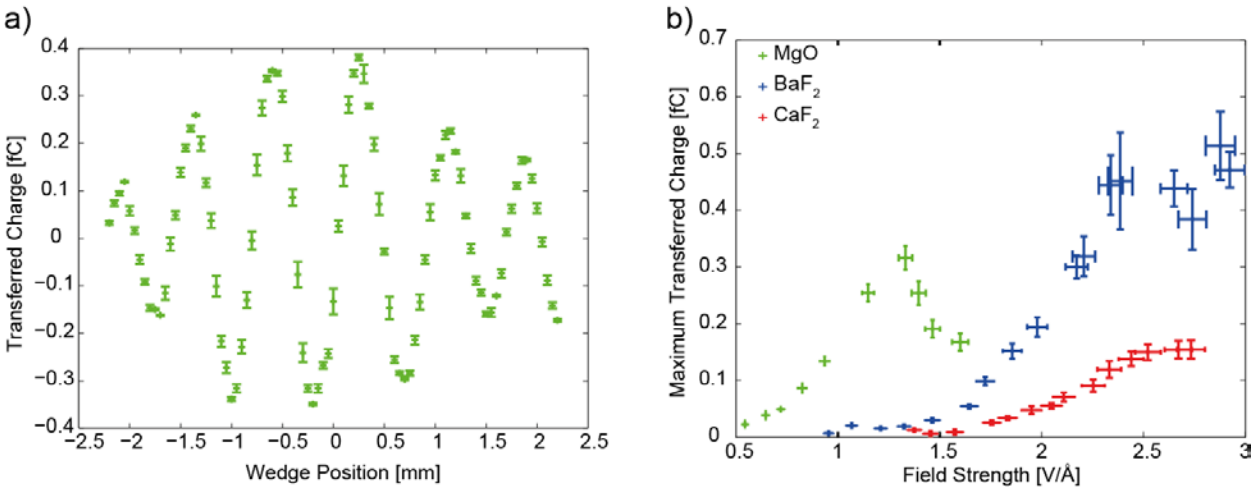

Fig. 2. Laser-Induced Transferred Charge. a) The transferred charge per pulse averaged over 1,500 shots shows a clear dependence on the position of the pair of fused silica wedges used to adjust the carrier envelope phase of the pulse. b) The signal amplitude as well as the critical field strength at which the signal sets in depends on the band gap of the material. The increase of the maximum transferred charge is shown for MgO, BaF_2, and CaF_2.

In contrast to previous experiments [1,4], the electrode gap in the reported measurements is much larger than the focus size. This raises the question how the laser-induced charge separation can be observed in the electronic circuit which has a response time of a few µs. Although our results do not allow a definite answer at this point, they suggest that trapping at the metal-dielectric interface does not play the predominant role in the current detection.

3. Conclusion and Outlook

We have shown that the amplitude of laser-induced ultrafast currents strongly depends on the band gap of the active material. In addition, the recent sample geometry allows for the detection of transferred charges for electrode gap sizes much bigger than the laser focus.

In a next step, we plan to use an infrared optical parametric amplifier (OPA) as a laser source. It operates at 2.1 µm carrier wavelength with a repetition rate of 3 kHz and can provide CEP-stable pulses with a sub-two-cycle duration and up to 1.2 mJ pulse energy [5].

By reducing the photon energy, the influence of low-order nonlinear effects is reduced, while at the same time the damage threshold of most materials is increased. This will enable us to investigate optically induced currents in semiconductor materials, which could be appealing for future optoelectronics applications.

4. References

[1] Schiffrin et al., “Optical-field-induced current in dielectrics”, Nature 493, 70–74 (2013)

[2] Ghimire et al., “Observation of high-order harmonic generation in a bulk crystal”, Nature Physics 7, 138-141 (2011)

[3] Schubert et al., “Sub-cycle control of terahertz high-harmonic generation by dynamical Bloch oscillations”, Nature Photonics 8, 119–123 (2014)

[4] Paasch-Colberg et al., “Solid-state light-phase detector”, Nature Photonics, DOI: 10.1038/nphoton.2013.348

[5] Deng et al., “Carrier-envelope-phase-stable, 1.2 mJ, 1.5 cycle laser pulses at 2.1 µm”, Optics Letters 37, 23, 4973-4975 (2012)