Time-domain optical pump - terahertz probe spectroscopic imager for carrier lifetime measurements in the pico- to microsecond regime

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***Abstract*—We demonstrate a spatially resolved method to measure carrier lifetimes and carrier distributions based on optical pump - terahertz probe spectroscopy. The pump-probe delay range spans from 600 ps to 200 µs. The spatial resolution is sub-wavelength being better than 50 µm ($< \lambda_{\text{center}}/6$ at 1 THz).**

I. Motivation

Adaptive metamaterials based on incorporation of thin semiconductors in plasmonic metamaterials are promising for implementation of large scale low cost terahertz scanners. For an adequate sample design, understanding the carrier dynamics in thin semiconductors is mandatory. The realized setup can be used to assess the applicability of thin semiconductors for adaptive metamaterials.

II. Experimental Setup

The demonstrated measurement technique is based on spatially resolved terahertz time-domain spectroscopy. The terahertz field was detected by electro-optic sampling in reflection. We achieved a spatial resolution of 50 µm [1]. For optical pumping we used a ns-laser that emitted pulses at a stable, but tunable time delay to the THz pulses. For synchronization, the Ti:Sa laser for the generation of THz radiation by photo-conductive switching served as a master clock. The master clock signal was split in two phase-coherent signals that triggered the generation of the ns-pump pulses and the generation of the THz pulses individually. By changing the phase delay of the two trigger signals the time delay between optical pump and THz pulses could be tuned. The repetition rate of the pump laser could be tuned from 5 – 200 kHz, which corresponds to a maximum delay of 200 µs. The smallest time step of $\Delta t_{min} = 600$ ps was limited by the used synchronization electronics. It should be noted at this point that the repetition rate of the THz pulses was 80 MHz. By using a Gaussian time window of adjustable width and delay we could gate the THz emission to obtain THz pulse trains of well-defined length. By gating the lock-in amplifier with the same gating signal we could define the temporal resolution and signal-to-noise ratio of the carrier lifetime measurements presented here. The optical pump power could be tuned smoothly from 0 to 4 W. The generated optical pulses had a temporal width of $w_t = 30$ ns at a center wavelength of 532 nm.

III. Results

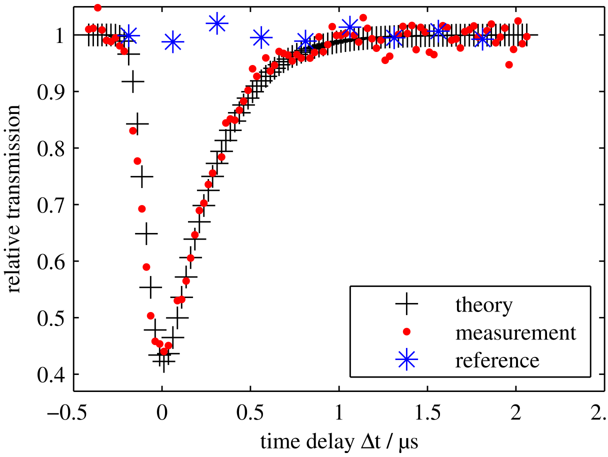

Fig. 1. Measured transmission amplitude vs pump time delay for a 30 µm thick silicon sample embedded in BCB. Red dots mark the measured and black crosses the analytically calculated transmission.

As proof of principle, we measured the lifetime of photo-induced carriers in silicon samples with different thicknesses [2]. For this purpose, we measured the amplitude transmission of the THz pulses through the sample in dependence on the pump-probe delay time. In Fig. 1, we only show the amplitude transmission (red dots) for silicon of 30 µm thickness. For mechanical stability we coated the silicon with 10 µm BCB on the front- and backside. The blue asterisks correspond to the reference amplitude transmission through the sample without pump beam. The black crosses depict the analytic calculation of the THz amplitude transmission. In this context, we calculated the time-dependent carrier density by solving the continuity equation and inserting the carrier density into the Drude model to derive the time-dependent permittivity of silicon and finally the amplitude transmission from the Fresnel equations. We see an excellent agreement between the measured (red dots) and the calculated transmission (black crosses). Based on our analytic model we retrieved the carrier lifetime τ from the width of the transmission dip in Fig. 1. For the photo-excited silicon of 30 µm thickness we obtained a carrier lifetime of $\tau = 230\,\text{ns}$. By aid of the high spatial resolution combined with the large available energy range we could evaluate the dependence of the carrier lifetime on the pump laser intensity for excitation of the photo-induced carriers, which is shown in Fig. 2. We measured the photo-induced carrier lifetime on three different sample locations that were separated by several hundred microns. For each point we measured multiple lifetime traces, as depicted in Fig. 1, from which we calculated the carrier lifetime. By increasing the pump pulse power, we were able to evaluate the pump intensity dependence of the photo-excited carrier lifetime. We note that for all three positions this dependence can be described with a linear function. The slope of this function is position-independent, while the y-intercept depends on the position. The lowest carrier lifetime ranges from 150 ns to 175 ns between position 3 and position 1. The power dependence of the carrier lifetime provides us with information on the bulk states as well as the density of the surface states. The high spatial resolution of this setup enables detailed checking of the homogeneity of bulk as well as surfaces states.

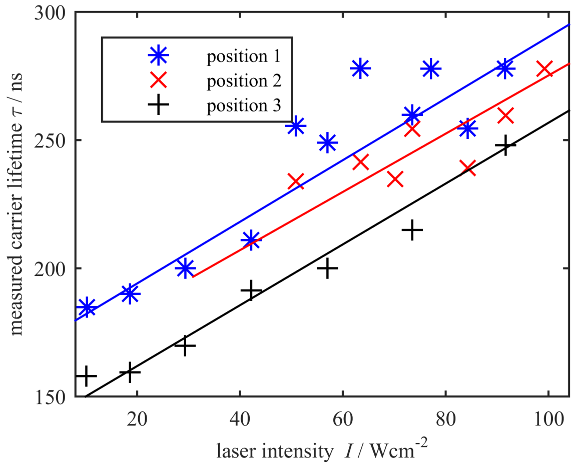

Fig. 2. Measured dependence of the carrier lifetime on the pump laser intensity for excitation of the photo-excited carriers for a 30 µm thick silicon sample embedded in BCB. We measured at three different positions of the sample, with a fixed repetition rate of 200 kHz.

In the presentation, we also report on additional measurements of the spatial distribution of the carrier lifetime $\tau(x, y)$ in the silicon sample. The high spatial resolution enables lifetime mapping of the sample by raster scanning the local carrier lifetime $\tau(x, y)$ As mentioned, the pump laser can be tuned to pulse energies up to $E = 800\,\mu\text{J}$, which provides us with a large energy range that can be used to measure the energy dependence of the carrier lifetime map $\tau(E, x, y)$.

IV. CONCLUSION

In conclusion, we demonstrated an imaging THz time-domain spectroscope for spatially resolved pump-probe experiments. The system is well suited for measuring the lifetime of photo-excited carriers in semiconductors on a scale from picoseconds to microseconds. By use of the spectroscope, we measured the lifetime of photo-induced free carriers in silicon samples with 30 µm thicknesses. We verified that the carrier lifetime depends on the intensity of the applied optical excitation pulse. Due to a spatial resolution of 50 µm, the THz time-domain spectroscope enables spatial mapping of the carrier lifetime distribution and thus investigations of the homogeneity of photo-excited materials.

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