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Mapping the distribution of photo-currents responsible for generation of terahertz pulses at semiconductor surfaces

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Abstract—Photo-excited charge carriers at semiconductor surfaces generate pulses of terahertz (THz) radiation. By mapping the spatial distribution of the THz radiation in the near-field and the angular emission pattern in the far-field, we link the THz generation process to the photo-current direction. We find that in-plane carrier dynamics play an important role and can even be the dominant source of THz radiation.

I. INTRODUCTION

Generation of terahertz (THz) radiation at semiconductor surfaces by short optical pulses is attributed to carrier dynamics in the photo-excited region. While the photo-carrier dynamics normal to the surface-plane have been regarded as the THz radiation origin[1], recent studies also took into account in-plane carrier dynamics[2,3]. Both photo-currents – in the surface plane and normal to it – can play a role in the generation of THz pulses, however, their individual contributions have not been evaluated yet.

In this study, we shed light onto the role of the in-place photo-carrier dynamics in the THz surface emission process. The photo-current direction is expected to affect the radiation pattern in the far-field as well as the field distribution in the near-field zone. We consider the excitation of semiconductor surfaces (InGaAs and GaAs) by 100 fs optical pulses (800nm) at normal incidence, and record the angular distribution of the emitted THz pulses. The far-field measurements are correlated with measurement of the near-field distribution, which allows to map the radiation sources in the surface plane. The experimental results are verified by simulating the electromagnetic pulse generation due to two idealized models of photo-current, in the surface plane and normal to it.

II. RESULTS

To produce THz radiation we use Fe-doped $In_{0.53}Ga_{0.47}As$ (Fe:InGaAs[4]). This material has been chosen because of a relatively strong THz emission efficiency measured in previous experiments. The angular THz emission pattern $E(\theta)$ is measured by a photo-conductive aperture probe placed in the far-field zone from the excitation source.[5] The 50 μm aperture selects emission within a narrow solid angle. By placing the detector at two different positions, as shown in Fig 1(a), we cover practically the entire range for angles from $0 \leq \theta \leq 90°$. Although the detected emission patterns above and below the surface are expected to be slightly different due to the substrate, the measurements allow us to determine the direction of the photo-current using the observed angles of maximum emission.

Amplitudes of THz pulses as a function of the emission angle θ are shown in Fig. 1(b). It is obvious that the maximum emission is neither in a direction parallel nor normal to the surface. This behavior cannot be explained by the emission due to the photo-current normal to the surface of the semiconductor.

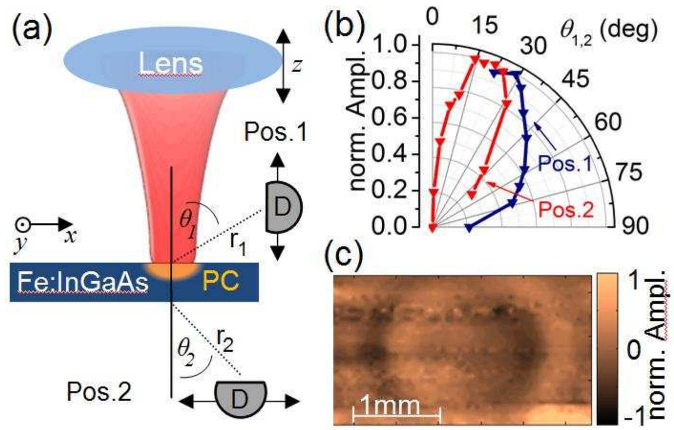

Fig. 1(a) Experimental system for detection of the angular emission pattern from the semiconductor surface; D shows the THz detector positions with respect to the photo-current (PC) region; (b) Angular emission patterns detected by the two detector positions (Pos. 1 and 2); both plots are normalized to their individual maxima; (c) Electric-field distribution measured in the xy-plane by the near-field detector positioned approximately 0.5mm from the surface.

There is a strong dependence of the amplitude and the directivity of the generated THz radiation on the diameter of the optical excitation spot. An excitation spot of ~300 μm produces a more directional emission, whereas a spot of ~60 μm produces practically an omnidirectional emission of THz pulses. The directional emission is several times larger in amplitude. We note that the effect of THz emission saturation does not affect the emission pattern in our experiments.

We explain the observed effects by including photo-currents within the surface plane in addition to the dynamics of photo-excited charge carriers normal to it. Both components of the photo-current have their individual contributions to the THz generation process.

We approximate the in-plane carrier dynamics by an annular distribution of dipole moments at the edge of the optical excitation area. If the size of the optical excitation area is smaller than the wavelength, the emission due to such current distribution is minimal. However it increases with the beam diameter as the interference between the dipoles on the opposite sides of the distribution changes from destructive to constructive.

To investigate the current distribution in the surface plane we map the generated THz wave in the near-field of the excitation area. Measuring the electric field distribution in the near-field of the photo-current plane can give us direct information about the photo-current distribution responsible for the THz emission.

The apparatus for this experiment is similar to Fig. 1 (a), with the near-field aperture probe positioned behind the sample with the substrate thinned. The probe is positioned ~500µm away from the photo-excitation plane. To obtain a two-dimensional map of the THz electric-field emitted from the surface, the excitation beam is raster-scanned in the xy-plane. Hence, the photo-current distribution within the semiconductor surface is raster-scanned, whereas the semiconductor itself and the probe remain in the same positions.

Fig. 2(c) shows the detected near-field image of the THz electric-field emitted from the material. One can clearly observe an annular electric-field pattern. Note that the probe is not sensitive to an electric-field polarized in the y-direction. It explains the fading field along the y-direction. The presence of this annular pattern suggests that the in-plane carrier dynamics at the edge of the excitation beam area may be producing a portion of THz radiation. Further analysis of the near-field distribution as well as the far-field emission pattern will be discussed.

In summary, we investigated the role of photo-carrier dynamics in the THz surface emission process. Based on measurements of the angular THz emission pattern and the near-field electric-field distribution we find that in-plane photo-carrier dynamics play an important role for THz surface emission and can even be the dominant emission mechanism.

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