Injection of CEP-controllable Current in Wide-bandgap Semiconductors: Effects of the Screening Field

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Abstract: A multiphoton mechanism of ultrafast current injection and control in GaN is studied. Analysis has shown that screening field of free charge carriers determines the field amplitude scaling law and strongly affects the charge-balancing phase.

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The progress in ultrafast lasers technology allows performing attosecond-scale time-resolved measurements of extremely nonlinear phenomena that occur when intense laser pulses interact with a solid. In a recent paper [1], it was demonstrated that electric current in a fused silica sample can be injected and controlled by the ultrashort pulse at intensities near to the damage threshold.

We study a similar phenomenon in GaN ($E_g \approx 3.2$ eV), exposed to a strong few-cycle laser field $F_L(t) = F_0 f(t)\cos(\omega t + \varphi_{CE})$ with a photon energy $\hbar\omega \approx 1.6$ eV and duration ~ 4 fs. The samples were fabricated lithographically in a flat geometry, with two unbiased gold electrodes connected with the measurement system (see Fig. 1).

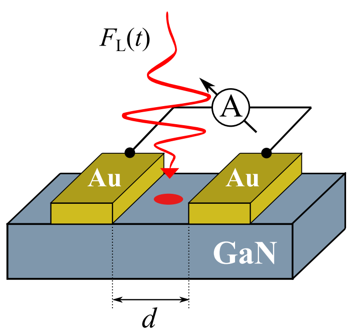

Fig. 1. A schematic picture of the sample: gold electrodes separated by distance d, fabricated on the GaN substrate.

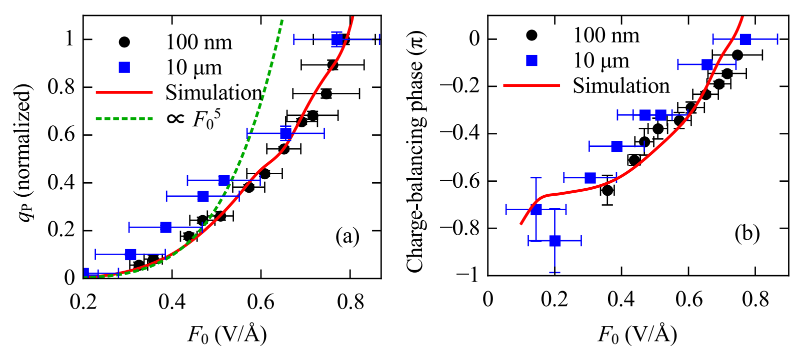

Fig. 2. (a) Dependence of transferred charge on the laser field amplitude. The measurements were done for different distances between the electrodes ($d = 100$ nm and 10 μm), and the simulations were performed according to Ref. [2]. (b) Intensity-dependent phase $\varphi_{CE}^{(0)}$, which yields a zero transferred charge.

The measurements yielded the values proportional to the transferred charge density

$$q_P \equiv \mathbf{P}(t \to \infty) = \int_{-\infty}^{\infty} \mathbf{J}(t)dt, \quad (1)$$

where **P** is the macroscopic polarization density, and **J** is the current density.

In the case of GaN, the ratio between the energy gap and photon energy is $n \approx 2$. Therefore, in the multiphoton regime of field-matter interaction the displaced charge should scale with the laser field amplitude as $q_P \propto F_0^{2n+1} = F_0^5$, due to the interference between two- and three-photon channels [2–4]. This scaling is successfully reproduced by simulations with linear screening (see the dotted line in Fig. 2a), where the field inside the solid $F(t)$ is assumed to be proportional to the laser field in the vacuum F_L. However, both experimental data and numerical simulations, where $F(t)$ is evaluated self-consistently with the equations for charge carrier dynamics, demonstrate a significant deviation from this law at field amplitudes higher than 0.45 V/Å.

Another important outcome is the dependence of the charge-balancing phase $\varphi_\mathrm{CE}^{(0)}$ on the laser field amplitude (see Fig. 2b). When the phase of the laser pulse is equal to $\varphi_\mathrm{CE}^{(0)}$, the electrodes collect an equal charge of opposite sign, which results in the zero net charge being measured. Dependence of this value on the field strength also appears only in the simulations with a self-consistent evaluation of the screening field.

Therefore, we conclude that both of these phenomena emerge from the interplay of two competing forces acting on electrons: the laser field and the screening field induced by the current of the excited charge carriers.

References

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