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Carrier dynamics around nano-scale Schottky contacts: a femtosecond near-field study

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Abstract

We report spatially and time-resolved measurements of ultrafast carrier dynamics around buried nano-scale Schottky contacts, performed with a novel femtosecond near-field scanning optical microscope. The experimental results are modeled by a self-consistent treatment of the drift–diffusion equation for the carriers and Poisson's equation for the built-in electric field. We show that the built-in field suppresses electron transport towards and trapping into the metal particles at lower optically excited carrier densities. In contrast, efficient electron trapping into the metal occurs at higher electron densities, which screen the built-in field, allowing for efficient transport of electrons towards the Schottky contact.

Keywords: Schottky nano-contacts; Near-field optics; Ultrafast carrier transport

In many metal–semiconductor composite materials Schottky contacts are formed at the interfaces between the semiconductor and the metal inclusions. Around the Schottky contacts electric fields and potentials exist even if no external bias field is applied [1]. Often, the presence of the metal inclusions gives rise to ultrafast carrier trapping. Ultrafast carrier trapping times have been observed in annealed low-temperature grown GaAs, which contains metallic As precipitates [2], and in GaAs in which nano-scale metal disks have been embedded by lithographic techniques [3,4]. The ultrafast trapping times make such materials very attractive for many applications in ultrafast electronics and optoelectronics [2]. A detailed understanding of carrier dynamics and carrier trapping is the basis for the further advancement of these technologies.

In this paper, we present a femtosecond near-field (NF) study of carrier dynamics in the vicinity of a *single* non-contacted nanometer-size tungsten (W) disk embedded in GaAs. Schottky contacts are formed at the W/GaAs interface [5], schematically shown in Fig. 1(a). Experimental data are obtained using a recently developed femtosecond-resolved near-field scanning optical microscope (NSOM) [6]. The measurements will be compared with a theoretical model based on a self-consistent treatment of the drift–diffusion and Poisson's equations. The spatially and temporally resolved measurements together with numerical simulations of the carrier dynamics give insight into the interplay between free carrier and field dynamics and carrier trapping around a *single* Schottky contact.

The investigated structure consists of a 500 nm GaInP layer as mechanical support at the bottom

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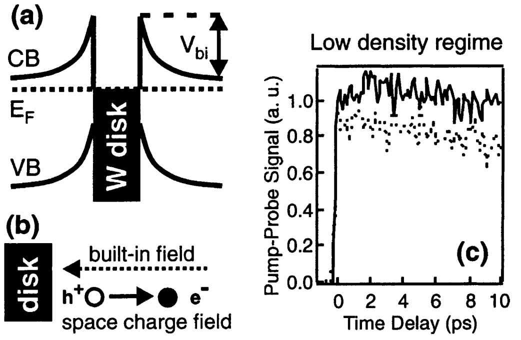

Fig. 1. (a) Schematic diagram of the GaAs band structure with the bent conduction and valence band (CB and VB, respectively) and the Fermi energy (E_F). (b) Schematic illustration of the built-in electric field and the space–charge field, resulting from electron–hole separation. (c) Low-density regime: NF pump-probe traces taken either over (dashed line) or 1 μm away (solid line) from the W disk.

followed by an absorbing region with an 80 nm GaAs layer, W disks with a thickness of 20 nm and ~80 nm diameter, and another 20 nm thick GaAs layer. A 20 nm thick GaInP protection layer has been grown on top to avoid the formation of surface traps. The structure has been fabricated by overgrowth of W disks, which have been produced in a rectangular pattern of 2 μm disk spacings by electron beam lithography and subsequent lift-off. The GaAs is n-doped (electron density $\sim 10^{16}$ cm^{-3}). The structure described above is obtained after etching off opaque layers to allow for transmission experiments. The thin top and active layers ensure good spatial resolution in NSOM measurements.

NF degenerate pump-probe measurements are performed at room temperature with 100 fs pulses from a 100 MHz mode-locked Ti:sapphire laser, centered at 1.46 eV. At this photon energy, the electrons yield the major contribution to the pump-probe signal [7]. The sample is excited from the bottom side with a pump beam of ~10 μm diameter. The pump-induced transmission changes are probed from the top side with pulses that are sent through a metal-coated NSOM fiber tip with an aperture <230 nm. To ensure high temporal resolution, the probe pulses are precompensated with a prism pair set-up in front of the fiber. A detailed description of the femtosecond NSOM can be found in [6].

We have performed numerical simulations in order to obtain a better understanding of the experimental NF pump-probe data. The electron and hole densities in the vicinity of a W disk are calculated with the drift–diffusion equation and Poisson's equation in a self-consistent way. The symmetry of the W disk structure allows us to use a one-dimensional model with the radius r in the W disk plane as the only space coordinate. The static band structure around the W disk before optical excitation and the built-in electric field are schematically illustrated in Fig. 1(a) and (b), respectively. The comparison of the simulation with the measured data yields a built-in potential $V_{bi} = 0.15$ eV. The details of the theoretical model are discussed in [8].

First, we will discuss the carrier and field dynamics for a low optically excited carrier density of 6×10^{15} cm^{-3}. Fig. 1(c) shows pump-probe traces taken either over or 1 μm away from a W disk. Apart from a small difference in amplitude both traces look the same. The curves are essentially constant within the 10 ps time window of the measurement. No fast dynamics is observed. We conclude that carrier trapping is inefficient despite the presence of a trapping center in the form of the W disk [4].

Fig. 2(a) shows a two-dimensional (2D) image of the pump-probe signal taken at a time delay of $\Delta t = 2$ ps. In the center of the image, where the W disk is located, a clear reduction of the signal is visible. Around this region, one observes a ring-shaped region in which the non-linear signal is slightly larger. The same features are seen in the 2D image of the calculated electron density in Fig. 2(b). The 2D images suggest electron transfer from the border of the disk to the outside region

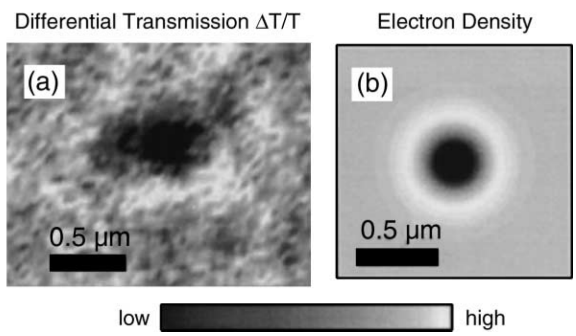

Fig. 2. Low-density regime: (a) 2D optical NF image of the differential transmission $\Delta T/T$ taken at a time delay $\Delta t = 2$ ps over a single W disk. (b) Calculated electron density for the experimental conditions of (a).

leading to a reduction of the electron density over the disk and to an enhancement of the density at a distance of 200 nm around the disk.

The results of the numerical simulations of the electric field, potential, electron and hole dynamics are shown in [8]. They reveal that, after optical excitation, the electron–hole pairs are separated by the electric field. The holes drift towards the disk, where they get trapped at the W/GaAs interface, whereas the electrons drift away from the disk. The spatially separated electrons and holes induce a space–charge field that is opposite to the built-in field; see the schematic picture of Fig. 1(b). However, the remaining electric field is still strong enough to lead to a non-negligible electron drift current away from the disk, which counteracts electron diffusion towards the disk. Thus, net electron transport to the disk is reduced and the trapping of electrons into the disk is inefficient, as seen from the pump-probe traces of Fig. 1(c). The ring-shaped region of enhanced electron density in Fig. 2 is observed at the edge of the depletion zone. At this position, the space–charge field compensates the built-in field and the total field crosses the zero line, thereby changing its sign [8]. This behavior of the field corresponds to the formation of a potential well in which the electrons accumulate.

In the high-density regime, we consider an excited carrier density of 7×10^{16}–$8 \times 10^{16}\ \mathrm{cm}^{-3}$, which is significantly higher than the doping level. In Fig. 3, pump-probe traces are shown which have been taken either over or 1 μm away from the disk. Over the disk, the signal decays within 7.5 ps to half of its initial value, significantly faster than away from the disk, where it takes 37 ps to reach the half-maximum

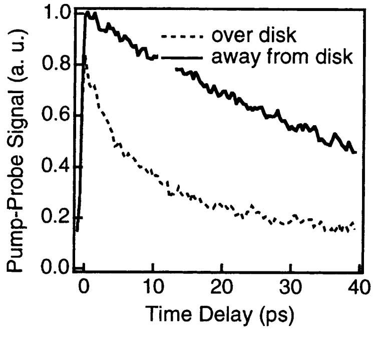

Fig. 3. High-density regime: NF pump-probe traces taken either over (dashed line) or 1 μm away (solid line) from the disk.

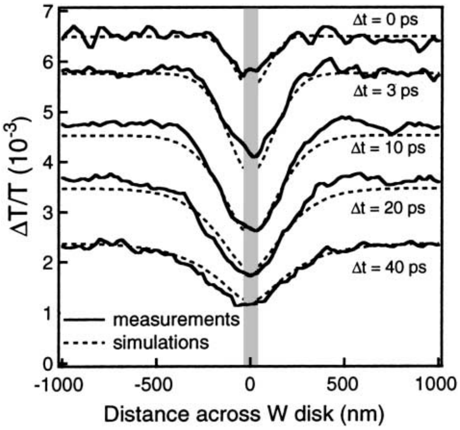

Fig. 4. High-density regime: line scans of the measured differential transmission signal (solid lines) and the calculated electron density (dashed lines) across a single tungsten disk for different time delays Δt. The gray bar marks the extension of the tungsten disk.

point. These data suggest that efficient electron trapping takes place in the high-density regime in contrast to the dynamics seen in the low-density regime.

More details of the spatiotemporal carrier dynamics can be inferred from direct measurements of the pump-probe signal versus distance across a single W disk for fixed time delays Δt. These data together with the calculated electron density are shown in Fig. 4. At zero time delay, the electron density is mainly reduced in the close vicinity of the W disk. With time, the shape of the traces changes and a reduction of the electron density is also observed farther away from the disk. The calculated electron density agrees very well with the measured pump-probe line scans. The data of Fig. 4 indicate that efficient transport of electrons towards the W disk takes place in the high-density regime.

From the experimental results of Figs. 3 and 4, we conclude that the electric field is strongly screened in the high-density regime, resulting in negligible drift of electrons away from the disk. This gives rise to efficient diffusive transport of electrons towards the W disk and efficient electron trapping. In fact, the calculation of the electric field [8] confirms that the field is strongly screened at short time delays due to the large number of trapped holes.

As the diffusion is faster for electrons than for holes, the charge of the initially trapped holes is slowly compensated, resulting in the slow recovery of the built-in electric field. Then, electron transport is again suppressed, leading to the offset of the traces seen in Fig. 3 at longer time delays.

In summary, we have shown that the coupling of carrier and field dynamics substantially affects carrier trapping in metal–semiconductor composite materials with buried Schottky contacts.

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