Visualization of ultrafast electron dynamics using time-resolved photoemission electron microscopy

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Abstract: We constructed a TR-PEEM which can directly image the photo-generated electron dynamics in semiconductor on nm and fs scales. Carrier transport properties relating to device performance, carrier lifetime, drift velocity and mobility, are investigated.

OCIS codes: (100.0118) Imaging ultrafast phenomena; (160.6000) Semiconductor materials; (110.0180) Microscopy

1. Introduction

The transport properties of charge carriers govern various characteristics of semiconductor devices, and thus, intensive studies have been devoted for the development of tools and techniques for probing of carrier dynamics. Recent developments of nanoscale semiconductor fabrication technology have made it possible to achieve quantum confinement of carrier movement. These achievements in semiconductor physics have also elevated the temporal and spatial resolution requirements of systems for the direct observation of carrier dynamics. Only a few methods, TR-SEM [1], TR-STM [2], and TR-PEEM [3,4] can examine ultrafast carrier dynamics with high spatial resolution. Until today, however, there no reports investigating the electron dynamics on fs and nm scales in semiconductor, because it has been thought to be difficult to do it due to space charging and surface charging effects.

Here we introduce a three-dimensional method for the direct observation of electron motion in semiconductors, which is conducted in two spatial dimensions and the time domain by utilizing time-resolved photoelectron emission microscopy (TR-PEEM) conducted with femtosecond laser pulses. By utilizing a repetition-rate-variable fs laser system and carefully optimizing laser parameters, lower the photon density per pulse to avoid charging and higher the repetition rate to gain more signal, we could observe photo-excited carrier dynamics on semiconductor surfaces in ultrafast timescale.

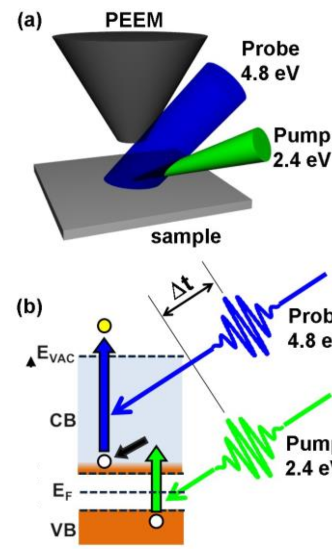

Fig. 1. Pump-probe scheme on a semiconductor surface

2. Experimental

Figure 1 provides experimental scheme for dynamical carrier measurements on a semiconductor surface. The pump pulses of 2.4 eV excite electrons into the conduction band, and the probe pulses of 4.8 eV is used to project the spatial distribution of photo-generated electrons density to the PEEM screen where photoemission intensity reflects the carrier density with the spatial resolution of 40 nm. By controlling the temporal delay between the two pulses, the electron dynamics in the conduction band could be visualized. The temporal resolution is defined by the cross-correlation of the two pulses (230 fs).

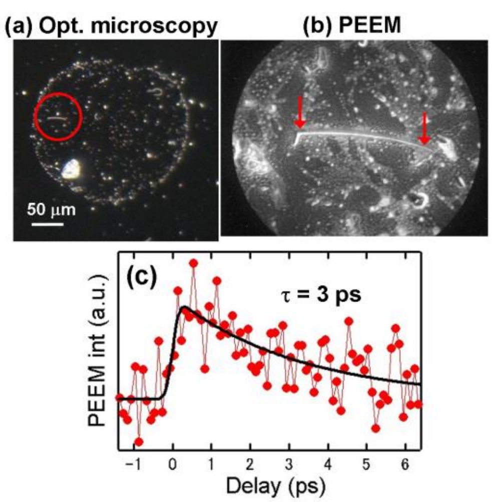

Fig. 2. Carrier lifetime in a single SiNW

3. Results

Using the constructed TR-PEEM, we observed the carrier relaxation and/or recombination on the timescale of sub-ps, and also observed the lateral motion of photo-generated electron bunch driven by the electric field gradient to estimate the drift velocity and the mobility [5].

3.1. Carrier lifetime in a Si nanowire (Fig. 2)

Here in Fig. 2 we show a demonstration of utilizing both high spatial and temporal resolutions as observing carrier lifetime in a single Si nano-wire (SiNW). Fig. 2 (a) is an optical microscopy image of SiNWs. One of them is highlighted by a red circle and an enlarged view is shown in Fig. 2 (b) as a PEEM image. In Fig. 2 (c), integrated PEEM intensity along NW is plotted against the delay time. Numerical fitting gives a fast annihilation of the carrier density in the wire in an exponential manner.

3.2. Electron drift velocity and mobility on a GaAs surface (Fig. 3)

This equipment can be also used to estimate electron drift velocity and mobility by directly imaging the motion of photo-generated electron bunch on a GaAs surface. Two metal electrodes are evaporated on to the surface and the electric field gradient (1.8 kV/cm) is applied to drive the electrons which are excited between the electrodes (Fig. 3 (a)). A PEEM image at 0 ps is shown in Fig. 3(b), in which the two electrodes are appeared at the top and bottom of the image, and the bright elliptical region at around the middle indicate the distribution of photo-generated electrons. Plots in Fig. 3 (c) are the intensity profiles along the vertical direction in PEEM images obtained at different pump-probe delay times of 20 ps, 40 ps, 100 ps, and 132 ps after the pumping. The lateral motion of the electron bunch to upwards is recognized by numerical fittings with a Gauss function to each plot. The peak position is plotted against delay time in Fig. 3 (d), and the slope by linear fit gives the drift velocity of 5.7 x 10^6 cm/s. By considering the mount of field gradient, 3200 $cm^2V^{-1}s^{-1}$ of the mobility has been estimated, which is relatively smaller than the bulk value of 8000 $cm^2V^{-1}s^{-1}$. This slightly smaller value obtained here can be due to surface roughness, which work as carrier trapping center to lower the drift velocity.

In summary, our newly developed TR-PEEM equipment using a repetition-rate-variable fs laser system can be used to evaluate some of the most important optical properties in semiconductor on nm and fs scales.

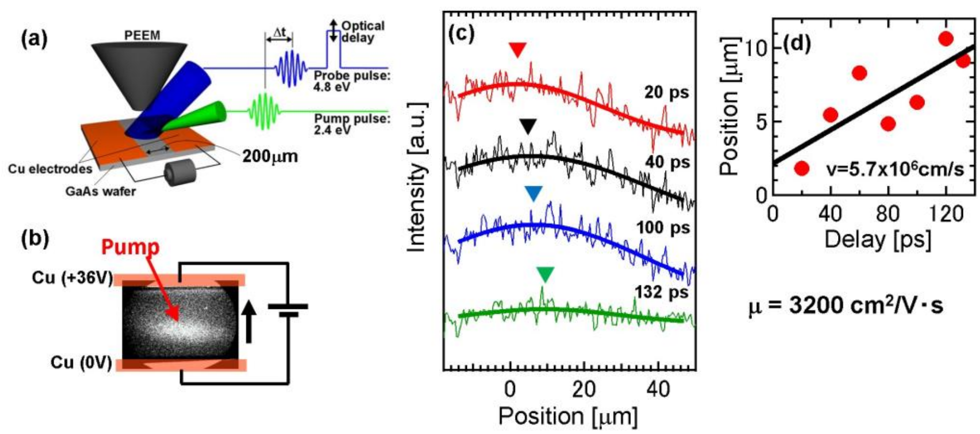

Fig. 3. Estimation of electron drift velocity and mobility

4. References

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