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Ebrahim Najafi

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Imaging Carrier Dynamics on the Surface of the N-type Silicon

Ebrahim Najafi

Chemistry and Chemical Engineering Division, California Institute of Technology

Pasadena, California 91125

Abstract

The nonequilibrium dynamics of carriers in semiconductors plays a major role in the performance and efficiency of the electronic and photovoltaic devices. In this study, we use the scanning ultrafast electron microscopy (SUEM) technique to study the surface photovoltage dynamics in doped silicon samples. We observe that the optical excitation of lightly doped n-type and p-type silicon as well as heavily doped n-type silicon increases the electron density on the surface. In contrast, the optical excitation of heavily doped p-type silicon increases the hole density on the surface. Furthermore, we show that the rise and the decay timescales of these events strongly depend on the doping concentration.

The optical pump-probe spectroscopy evaluates the dynamics of charge carriers in semiconductors by measuring the transient surface reflectivity or transmission following an optical excitation. Since the optical properties of semiconductors depend strongly on the free carrier distribution and temperature, the recorded signal mirrors the temporal evolution of the excited state towards the ground state [1]. This allows the investigation of intermediate pathways that carriers undertake, including energy and momentum relaxation, carrier-phonon scattering, diffusion and recombination. While the optical pump-probe spectroscopy provides valuable insights into the electronic landscape of semiconductors, it lacks a sufficient spatial resolution; thus, measuring only the averaged dynamics over a large area and ignoring those that take place at the surfaces and interfaces.

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In this work, we introduce the scanning ultrafast electron microscopy (SUEM) technique, which allows the "direct image" of the spatiotemporal dynamics of carriers [2, 3]. Specifically, we report the SUEM imaging of the surface photovoltage (SPV) dynamics in silicon, which results from the transient repopulation of the surface states by minority carriers [4]. We show that the super-bandgap excitation of the lightly doped n-type silicon increases the electron density on the surface; in contrast, the optical excitation increases the hole density on the surface of the heavily doped n-type silicon. Furthermore, we show that the rise and the decay timescales of these events are strong dependent on the doping concentration.

The silicon samples studied for this experiment were purchased from MTI corp. The samples were cleaved and immediately transferred into the SUEM chamber where the vacuum was maintained at 2×10^{-7} torr. The design and operation of the SUEM were explained previously, but a short description follows. The SUEM consists of a conventional SEM combined with a laser source, which produces femotsecond IR pulses (300 fs, 1030 nm). These IR pulses are split to produce green (515 nm) and UV (257 nm) pulses though harmonic generation. The former is guided into the SEM to excite samples, while the latter is directed towards the photocathode to produce short electron pulses from the field emission tip. The time delay between the green and electron pulses is synchronized by a mechanical stage, which provides 3.3 ns interval at 700 fs steps. The electron pulses are then accelerated to 30 kV and focused on the sample by electrostatic lenses to produce secondary electrons (SEs) from the top $2 - 10$ nm of the surface, which are then collected by the SE detector for every pixel.

To form an image at a particular time delay, the surface was scanned by the electron probe focused into a 200 nm spot, which was sufficient to capture spatial details in this study. To remove the background contributions and to enhance the dynamic signal, the image of the

sample in the ground state ($t \ll 0$) was subtracted from the dynamic images recorded at various time delays ($t > 0$). This produced so-called "contrast images", in which the bright or dark signals were interpreted as increases in electron and hole densities, respectively.

Figure 1 shows the transient response of the lightly doped (left panel) and heavily doped (right panel) N-type silicon samples. In both cases, there is no observable dynamics in the negative time since the samples exist in the ground state. Following the optical excitation, a bright contrast emerges on the surfaces of the lightly doped sample with an intensity that systematically increases with time. On the contrary, the heavily doped sample shows a dark contrast after optical excitation, indicative of an increase in the hole density on the surface. The contrast is stronger and shows a larger spatial extent in the heavily doped sample simply because the larger doping concentration reduces the bandgap and increase the overlap between the wave-functions of the initial and the final states; thereby increasing the absorption cross-section [5]. At later times, both the bright and dark contrasts decrease as carriers recombine and the systems evolve towards the ground state.

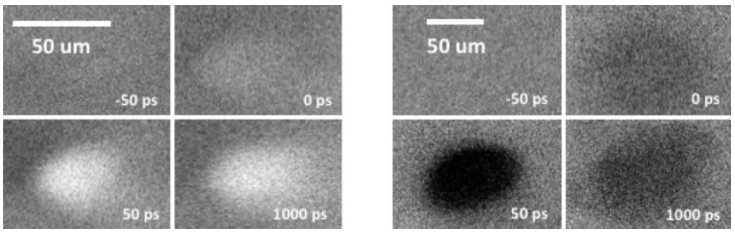

Figure 1- The spatiotemporal dynamics of the lightly doped (left panel) and heavily doped (right panel) silicon imaged at various time delays.

Figure 2 plots the contrasts for the lightly doped (upper graph) and the heavily doped (lower graph) samples at the crossover at various time delays. The initial rise in both cases was successfully fitted by a single exponential function. However, the excitation extended significantly in the latter sample, as indicated by the time constants determined to be 6 ps and 80 ps, respectively. This significant difference is attributed to the large band bending in the heavily doped silicon which provide a continuing stream of minority carriers toward the surface. The relaxation of both systems showed even more complex behavior which we attributed to different defect levels in these samples.

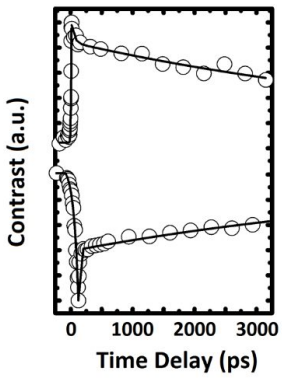

Figure 2- The spatiotemporal dynamics of lightly doped (left panel) and heavily doped (right panel) silicon at various time delays.

In conclusion, we studied the spatiotemporal dynamics of charge carriers in doped silicon by imaging the carriers in both space and time. We observed that the underlying dynamics, excitation and relaxation events, were strongly dependent on the doping concentration.

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