Visualization of photoexcited free carriers by scanning near-field millimeter-wave microscopy

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Visualization of transition phenomena of photoexcited free carriers by scanning near-field millimeter-wave microscopy has been demonstrated. A scanning millimeter-wave microscope using a metal slit-type probe and an image reconstruction algorithm based on computerized tomographic imaging has been used in the experiment to achieve two-dimensional time-resolved imaging. Experiments performed at 60 GHz ($\lambda = 5$ mm) under room temperature conditions show that generation, extinction, and diffusion processes of photoexcited free carriers generated in the silicon layer of a silicon on quartz substrate can be imaged with a time division of one nanosecond and a spatial resolution of 110 μm ($\sim\lambda/45$). © *2000 American Institute of Physics.* [S0003-6951(00)00927-X]

Because millimeter and submillimeter waves are strongly affected by the free carriers in a plasma,[1] they can be used as a valuable diagnostic tool. This has been particularly true for the fusion research community. It is possible to directly image the plasma to form a two-dimensional image of the plasma density. Similarly, it is possible to make use of the same principle to image free carriers in the other enviroments. Since scanning near-field microscopy was first demonstrated at microwave frequencies by Ash and Nicholls,[2] the technique has been extended to the optical region.[3] For this part of the electromagnetic spectrum, this technique achieved a resolution much less than a wavelength, λ, for a variety of experimental configurations. The unique properties of millimeter and submillimeter waves when combined with scanning near-field microscopy enables direct observation of the dynamics of free carriers such as generation, diffusion, and extinction processes in semiconductors with subwavelength spatial resolution. We report here time-resolved imaging of photoexcited free carriers in silicon by scanning near-field millimeter-wave microscopy. Unlike free carrier imaging carried via photoluminescence in the optical region,[4] the method presented here has the distinct advantage that the direct observation of free carriers can be carried out under room temperature conditions.

The time-resolved imaging of photoexcited free carriers described here was carried out at a millimeter-wave frequency of 60 GHz ($\lambda = 5$ mm) under room temperature conditions. Figure 1(a) shows our experimental setup. We have demonstrated this scanning near-field millimeter-wave microscopy which utilizes a metal slit at the end of a tapered rectangular waveguide as a scanning probe, and an image reconstruction algorithm based on computerized tomographic (CT) imaging to reconstruct two-dimensional near-field images with subwavelength resolutions for all directions.[5] The length of the slit is identical to the width of the original waveguide (WR-19) but the waveguide height is tapered down to 80 μm ($\lambda/60$), which is the width of the slit aperture. The slit probe can be operated in the TE_{10} mode, and

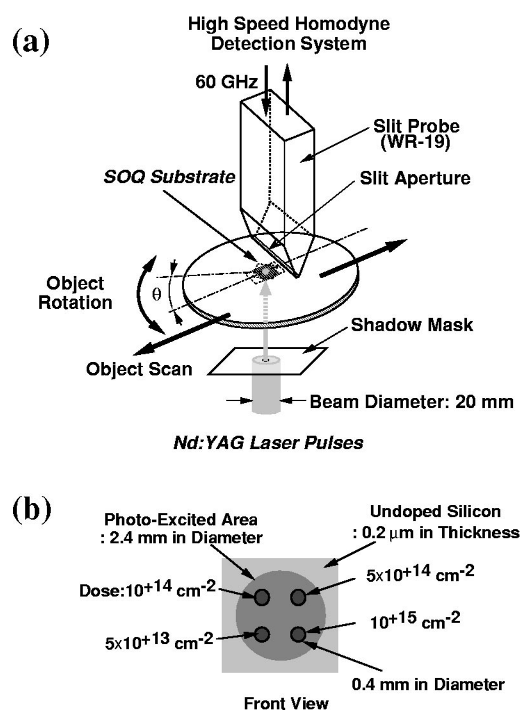

FIG. 1. Experimental scheme for visualizing transition phenomena of photoexcited free carriers in reflection mode: (a) experimental setup and (b) sample configuration. The experimental conditions in data acquisition are as follows: sampling interval for linear scan is 60 μm, sampling points for linear scan, 74 points, sampling interval for rotational scan, 2.43°, total number of linear scans, 74, and probe-to-object separation, 10 μm.

[a)]Present address: Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-Ku, Sendai 980-8577, Japan; electronic mail: nozokido@riec.tohoku.ac.jp thus results in high transmission efficiency, even when the slit width is exceedingly small. The slit probe is suitable for measuring high-speed phenomena because of its much higher transmission efficiency and wider frequency bandwidth than conventional point-type probes.[6] The power transmission coefficient of the slit probe used in the experiment is estimated as 20% at 60 GHz and the frequency bandwidth exceeds 20 GHz.[7] The probe was mounted on a fixed stage and connected to a high-speed homodyne detection system possessing a response time of 0.4 ns. Millimeter-wave radiation is transmitted to the probe, the reflected signal from the probe down converted and its temporal variation monitored by an oscilloscope. The sample being imaged is scanned under the probe at a constant separation via rotational and linear stages driven by stepping motors. Computer control is used to synchronize the homodyne system and the sample scanner. For this investigation the sample chosen was a silicon on quartz (SOQ) substrate.[8] Figure 1(b) shows the sample configuration. The thickness of the undoped thin silicon layer and the quartz substrate were 0.2 μm and 1.2 mm, respectively. Ion bombardment was used to give the silicon an effective dose of $5\times10^{13}\sim10^{15}\,cm^{-2}$, 100 keV Ar^+ ions were used. Free carriers in the silicon layer were generated using optical pulses from a Q-switched Nd:YAG laser which was directed through the quartz layer. The Nd:YAG laser wavelength was 355 nm, the repetition rate was 10 Hz, the pulse width was 5 ns. A shadow mask with a 2.4-mm-diameter hole was inserted in the laser beam path, and the mask was fixed to the scanner. This configuration allowed to uniformly illuminate a 2.4-mm-diameter region on the SOQ substrate during the object scan. Transmitted energy of the optical pulse through the hole was 0.8 mJ and the density of free carriers generated was estimated to be as high as $10^{+17}\,cm^{-3}$ (Ref. 9). Linear scanning of the object was carried out for different object-rotation angles, θ, as shown in Fig. 1(a). This scan method is quite different from the raster scanning technique used in other conventional scanning near-field microscopes. During the object scans, waveforms from the oscilloscope were stored against each position of the object. The stored waveforms are then arranged and processed into time-resolved images by the filtered back-projection method,[10] which is the most commonly used image reconstruction method in CT imaging. This scan and image reconstruction method enable us to obtain images with a spatial resolution of 110 μm ($\sim\lambda/45$) for all directions without astigmatism.[5] The minimum carier density in silicon which can be detectable with this system is estimated to be $\sim10^{14}/cm^{-3}$ (Ref. 11).

Figure 2 shows the reconstructed images. In this figure, the circle in the image at 0 ns shows the photoexcited region. Free carrier generation and extinction processes can be clearly seen. The diffusion process of free carriers out of the photoexcited region is also observed. In addition, temporal information regarding image intensity can be reconstructed as shown in Fig. 3. The image intensities at five distinct points for varying doses of Ar^+ ions are illustrated. Since the ion bombarded region is damaged and has some defects, and is therefore under photoexcitation, the carrier lifetime is shorter than in the undamaged region. This leads to lower carrier density and a lower millimeter-wave reflectance, resulting in reduced image intensity. The time variations in Fig. 3 show that for higher doses of Ar^+ ions the density of free carriers generated at the corresponding point is reduced, as is their lifetime. An equivalent circuit model describing the interaction between the slit probe and photoexcited free carriers shows that the image intensity is nearly proportional to the logarithm of the carrier density. From this formulation, the carrier lifetimes in the silicon layer were evaluated to be 5 and 10 ns, respectively, for the ion bombarded and unbombarded regions of the silicon layer, which are $\sim10^3$ times smaller in value than that in undoped bulk silicon.[9]

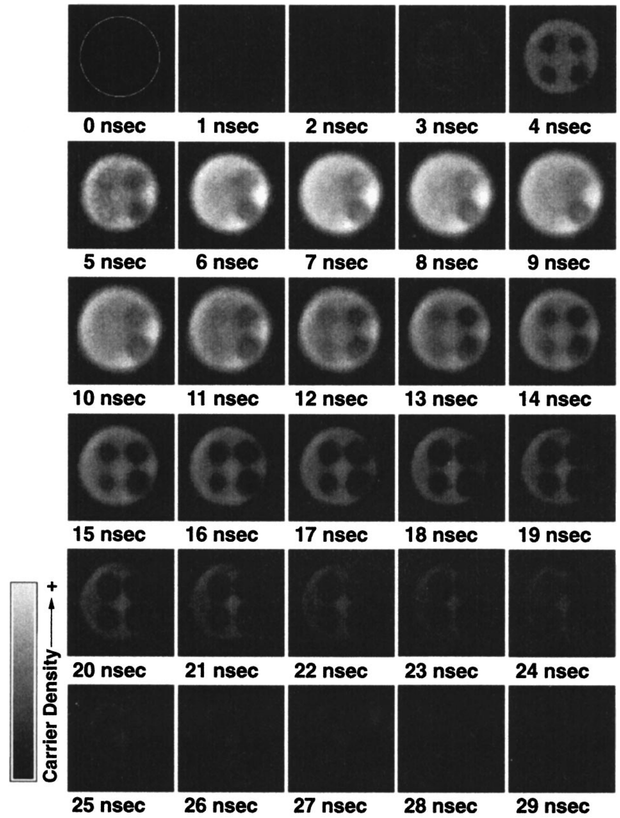

FIG. 2. Temporal evolution of photoexcited free carrier distribution. The image size is 3220 μm$\times$3220 μm. The time under each image indicates the time after the photoexcitation began. The time division is 1 ns.

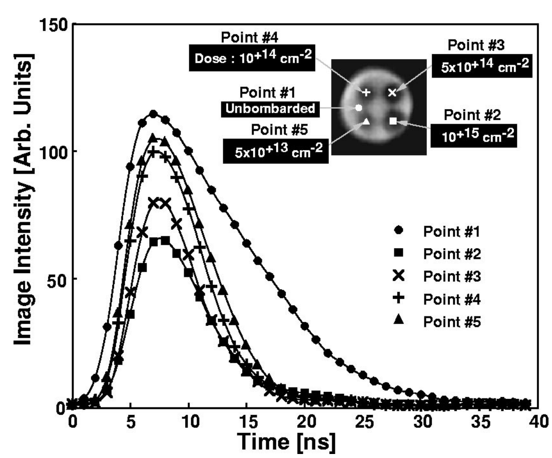

FIG. 3. Temporal changes of image intensities. Point 1 is the unbombarded region, and Points 2–5 are the ion bombarded regions with doses of 5×10^{13}, 10^{14}, 5×10^{14}, and $10^{15}\,cm^{-2}$, respectively.

In conclusion, we have demonstrated two-dimensional time-resolved imaging of photoexcited free carriers in silicon by scanning near-field millimeter-wave microscopy. Experiments performed at 60 GHz ($\lambda = 5$ mm) under room temperature conditions show that generation, diffusion, and extinction processes of free carriers in a silicon substrate can be imaged with a time division of one nanosecond and a spatial resolution of 110 μm ($\sim\lambda/45$). Although a SOQ substrate was used for this demonstration, the technique presented here should be applicable to visualize carrier transport mechanisms in various kinds of semiconductor geometries and devices.

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