Visualizing an Artificial Recombination Pattern Formed by Localized Illumination in a Semiconductor

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Electrically detected magnetic resonance (EDMR) imaging is a method to investigate the distribution of a paramagnetic recombination center in semiconductor materials. The EDMR image of a rectangular silicon plate (width, 2 mm; length, 20 mm; thickness, 0.5 mm; resistance, 5 kΩ·cm) was obtained under partial light illumination that was limited to the center of the sample. The sample had a native uniform distribution of paramagnetic recombination center and showed no EDMR signal without illumination. Low or high intensity area was located at the center (illuminated area) or sides (nonilluminated area) in the EDMR image. The patterns were the same when the opposite direction of the DC current was applied to the sample.

Electrically detected magnetic resonance (EDMR) spectroscopy is a method to analyze semiconductor materials by detecting the change in conductivity of a sample caused by ESR.[1,2] This method makes it possible to perform a highly sensitive and selective detection of paramagnetic recombination centers formed by lattice defects or impurities in the semiconductor material. The enhancement of EDMR sensitivity has been explained by an electron–hole pair model, where an electron or a hole forms a localized pair with a recombination center in a triplet and a singlet in a static magnetic field before recombination.[3–9] We developed an EDMR imaging system operating at an ESR frequency of 900 MHz under field gradients.[10,11] By using this system, an EDMR image of a 20-mm-square silicon plate under uniform light illumination had been obtained, which was provided spatial information on the position of the paramagnetic recombination center in the sample. In this study, an artificial recombination pattern of a sample formed by localized illumination was visualized.

The sample material, a 3.5-inch silicon wafer, was cut into long rectangular plate (width, 2 mm; length, 20 mm; thickness, 0.5 mm; resistance, 5 kΩ·cm). Since the amount of the doped impurity in this sample was very small, the band gap of the sample was similar to that of the pure silicon crystal, which can be excited by a photon at short wavelength less than 1100 nm. Electrodes were constructed on both sides of this rectangular plate leaving an open area (15 mm in length). Chromium was deposited to a thickness of 40 nm onto the surface of a polished silicon plate to produce electrodes with ohmic contact. Gold was deposited onto the chromium layer to a thickness of 200 nm. For efficient irradiation to the sample with an alternating magnetic field (B_1) at the ESR frequency, a bridged loop-gap resonator (BLGR)[12] was used. The field gradient was applied in the z–y plane, which was rotated by 10 degrees after each acquisition to obtain an averaged spectrum (accumulation number, 81). Here

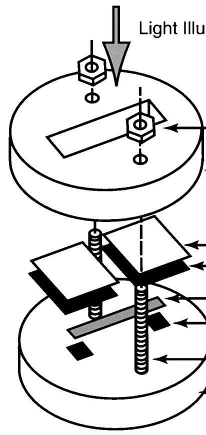

Figure 1. Schema of the sample setting.

the z axis and the static magnetic field (B_0) are coincident; and the x or y axis is the parallel or perpendicular to B_1, respectively. Each 1-D distribution of the EDMR signal intensity was obtained by deconvolution of the signals observed in the magnetic field gradient, on the basis of the EDMR spectrum in a uniform magnetic field. The 2-D distribution of EDMR signal intensity was reconstructed from the 1-D projections. The spatial resolution was 1.9 mm. The sample was placed at the center of the BLGR and the change in voltage between the electrodes of the sample was detected at a constant DC bias current (10 μA). The schema of the sample setting was shown in Figure 1. Two Teflon holders sandwiched the sample. A 16×9-mm^2 window in the center of one holder allowed light illumination. A pair of gold-plated copper contacts was placed on the other holder. Carbon blended black plastic film was used to mask the sample. Teflon film covered the back mask film to prevent heating by the light illumination. The resistance of the carbon blended film was so high ($>10^7$ Ω·cm), that the influence to the B_1 was negligible. A halogen incandescent lamp was used to illuminate the sample. Infrared radiation was inhibited with a glass filter (KG-1;Edmund Optics, Japan; cutoff, 700 nm). The peak wavelength of illumination under these conditions was 608 nm. A decrease in photoconductivity under ESR conditions was obtained as the EDMR signal at room temperature.

The EDMR signal was not observed when the sample was not illuminated. However, the distributions of EDMR signal intensity of two different samples under uniform light illumination were obtained without the mask film as shown in Figures 2a and 2b. Although the two samples were cut from the same wafer, different EDMR images were obtained. It is thought that these patterns show different native distributions of paramagnetic recombination centers in these samples because the experimental conditions were the same for each sample. Figures 2c through 2f show EDMR images of the sample with a relatively uniform distribution of paramagnetic recombination centers (the sample in Figure 2a) under partial illumination by using the mask film, forming an artificial recombination pattern. The illumination was limited to a center region (width, 2 mm; length, 4 mm) of the sample. In these pictures, the center and sides appear as low and high intensity areas, respectively. The patterns remained the same when the orientation of the sample was changed (pair of (c) and (e), or (d) and (f) in Figure 2), indicating that the B_1 distribution was uniform and that the image is reproducible. The patterns were the same even the electrical polarity was reversed (pair of c and d or e and f in Figure 2).

Although an excess carrier was generated only in the illuminated area, it is thought that diffusion of this excess carrier causes high intensity in the nonilluminated area. Because the recombination center forms a pair with one of the conduction electrons or holes: a spatial differences in density distributions between the conduction electron and the hole is predicted when the photoexcited hole moves in the same direction as the applied DC electric field and the electron moves in the opposite direction. Thus different EDMR images might be expected when the polarity is reversed. However, under the conditions in this study (electrical field almost 1 V/cm), the conduction electrons and holes are diffused uniformly within the sample, so that no differences in EDMR images are observed for different polarities.

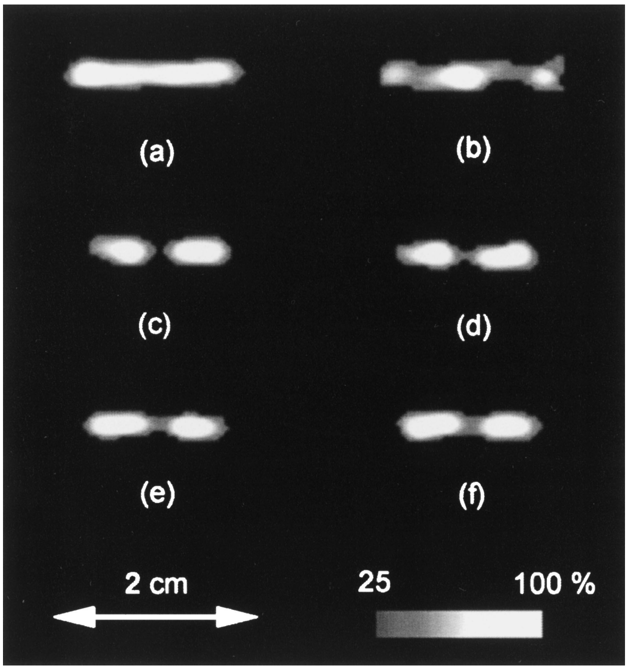

Figure 2. EDMR images of part of a 3.5-inch silicon wafer: (a) and (b) show the native distributions of the recombination center of two different samples under uniform light illumination. Both samples were cut from the same wafer. (c)–(f) show EDMR images of an artificial recombination pattern in the sample in (a), which originally had paramagnetic recombination centers that were relatively uniform distributed. The artificial pattern was generated by partial illumination (limited to a 2×4-mm area in the center of the sample). Electric field polarity was reversed in (c) and (d), and (e) and (f); the sample was rotated 180 degrees in (c) and (e), and (d) and (f). These images were reconstructed from 18 of 1-D projections under a linear field gradient (2 mT/cm) along the y and z axes at changing direction of 10 degree steps. Each projection was obtained from 81 time accumulation sweeps (sweep time, 1.9 s; sweep width, 15 mT). The magnetic field was modulated at 362 Hz for lock-in detection. The microwave frequency and power were 890 MHz and 1 W, respectively.

When the excited carrier does not diffuse uniformly, the resistance of the illuminated area might be very low, so that the influence of the illuminated area to the total resistance might be less, causing low intensity in the illuminated area. However, the excess carrier probably diffuses uniformly throughout the sample in equilibrium conditions. The infrared radiation was cut by using a filter and sufficient pre-heat time (2 h) by light illumination was allowed; so local decreases in resistance in the illuminated area of the sample due to heat were negligible. The change in resistance caused by ESR in the illuminated area is, therefore, relatively smaller, which cannot explain the reason for the low intensity in the illuminated area. A possible explanation for this phenomenon is that the photoexcitation occurred efficiently at the recombination center, separating the electron–hole pairs in the illuminated area. It is difficult to prove this by experiments because many of the parameters concerning photoexcitation and the recombination process must be controlled. However, we believe that EDMR imaging by localized illumination can become a tool by which the characteristics of semiconductors can be estimated because the parameters noted above are related to them.

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