Nonresonant spin-dependent conductivity in silicon

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A nonresonant change has been discovered in the photoconductivity of irradiated silicon crystals in a weak magnetic field. This new effect is shown to result from a spin-dependent recombination of photoexcited carriers through triplet centers. A change in the photoconductivity in the absence of a resonant alternating magnetic field arises at anticrossing points of magnetic sublevels of triplet centers.

Experiments on various n- and p-type silicon crystals irradiated by electrons or γ rays reveal a change in the photoconductivity in a weak magnetic field, in the form of narrow lines similar to ESR signals. This change in photoconductivity is observed in the absence of a resonant alternating magnetic field, detected from the change in the Q of the resonator of an ESR spectrometer.

Figure 1 shows signals of the change in the resonator Q due to a change in the photoconductivity of silicon crystals as recorded by a 3-cm ESR spectrometer. The second derivative of the signals was recorded.

In pure silicon crystals grown by crucible-free zone melting and containing oxygen at a concentration $N_0 < 10^{16}$ cm^{-3}, a change in the photoconductivity is observed after γ irradiation in a dose $\sim 10^{15}$ cm^{-2} when the sample is placed in a magnetic field $H = 387.6$ G directed parallel to a $\langle 111 \rangle$ direction of the crystal (Fig. 1a). In silicon containing oxygen ($N_0 \sim 10^{18}$ cm^{-3}) irradiated with γ rays to a dose $\sim 10^{14}$ cm^{-2} we also observe a change in the photoconductivity, but in this case in a magnetic field $H = 351.6$ G in the orientation $H \| \langle 110 \rangle$ (Fig. 1b). Similar signals are found in silicon crystals bombarded by 1-MeV electrons in doses from 10^{13} cm^{-2} to 10^{17} cm^{-2}. No signals are observed in samples that are not irradiated.

The effect has some general features. The lines shown in Fig. 1 are observed only when the crystals are illuminated with light in their intrinsic absorption region. The positions and intensities of the lines do not depend on the frequency or amplitude of the microwave field in the resonator. A deviation of the magnetic field from the $\langle 111 \rangle$ or $\langle 110 \rangle$ axis of the crystals results in a broadening and weakening of the lines. At an angular deviation of $\pm 5\%$, the lines are no longer observed. The sign of the observed signals is opposite that of ordinary ESR absorption signals and corresponds to an increase in the Q of the resonator of the rf spectrometer. The signals are observed to reach a maximum intensity in the temperature interval 20–30 K.

Examination of all the experimental results suggests that the change in the resonator Q results from a change in the photoconductivity of the sample which is caused by a spin-dependent recombination of the photoexcited carriers through paramagnetic centers that have "singularities" at magnetic fields of 387.6 G and 351.6 G. These centers might be triplet centers which have level anticrossing points at these magnetic

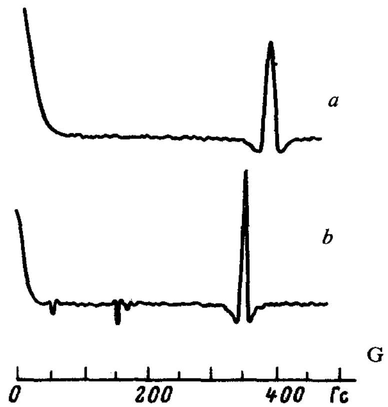

FIG. 1. Signals showing the change in the photoconductivity of γ-irradiated silicon crystals. *a*—Silicon without oxygen, $H \| \langle 111 \rangle$; *b*—silicon containing oxygen $H \| \langle 111 \rangle$.

fields, and the $\langle 111 \rangle$ and $\langle 110 \rangle$ axes might be the principal symmetry axes of these centers.

Silicon containing oxygen does in fact exhibit the Si-SL1 ESR spectrum,[1] which corresponds to triplet excited states of complexes of an oxygen atom with a vacancy, which form during irradiation, with constants $D = 352$ G and $E = 7.7$ G. The Si-SL1 center is almost axisymmetric, with a $\langle 110 \rangle$ symmetry axis, and a level anticrossing point ~ 352 G. The line in Fig. 1*b* can accordingly be attributed to this center.

Silicon not containing oxygen exhibits an ESR spectrum of triplet centers, designated[2] Si-PT1, which has a $\langle 111 \rangle$ symmetry axis and a constant $D = 430$ G. The constant E could not be determined, since the ESR spectrum of the centers is observed only in orientations near $H \| \langle 111 \rangle$. If we attribute the line in Fig. 1*a* to a Si-PT1 center, we can determine the constant E from the relation $H_0^2 D^2 - E^2$, where $H_0 = 387.6$ G is the anticrossing point of the $|0\rangle$ and $|-1\rangle$ levels of the Si-PT1 centers, with $E = 183$ G.

To check whether the observed lines of a nonresonant change in the photoconductivity of the irradiated crystals were in fact associated with anticrossing points of magnetic sublevels of triplet centers, we carried out some experiments on a resonant saturation of the transitions of the triplet centers near the level anticrossing points, and we measured the spin-dependent recombination through these centers. The resonant transitions were saturated by an alternating magnetic field with a frequency between 135 and 900 MHz, produced by a coil in the resonator of the microwave spectrometer near the sample.

Part *a* in Fig. 2 is the diagram of energy levels of the Si-PT1 center calculated from the values found for the parameters D and E, while part *b* is the observed ESR spectrum, found from the change in the resonator Q. The frequency of the alternating magnetic field was 300 MHz. The resonant lines coincide well with the transitions between the calculated levels. It should be noted that the amplitudes of the resonant lines in these experiments were essentially independent of the frequency of the alternating field over the range 135–900 MHz.

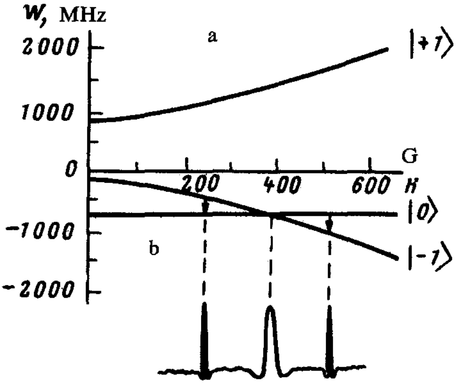

FIG. 2. a —Energy-level diagram of the Si-PT1 center in a magnetic field $H \parallel \langle 111 \rangle$; b — ESR spectrum found at a resonant-field frequency 300 MHz.

The effects of the spin-dependent recombination may accordingly arise not only during resonant saturation of ESR transitions but also in the absence of a resonant field, at the "singularities" of the energy spectrum of paramagnetic centers, such as the anticrossing points of magnetic sublevels of triplet centers, where the $|-1\rangle$ and $|0\rangle$ states are mixed. The same mixing, which occurs in a zero magnetic field, is apparently responsible for the change in the photoconductivity in magnetic fields 0–50 G (Fig. 1). In the spectrum in Fig. 1*b* we also see some faint lines with a different phase. These lines belong to other paramagnetic centers in the crystal, whose nature has not yet been determined exactly.

We can draw some conclusions from this study. A spin-dependent recombination through triplet centers in a weak magnetic field in silicon crystals containing radiation-induced defects has been observed for the first time. A new effect has been discovered: a nonresonant change in the photoconductivity of the crystals in magnetic fields corresponding to anticrossing points of the magnetic sublevels of triplet centers. So far, spin-dependent recombination in crystalline silicon has been studied at only a limited number of centers: surface centers[3] and dislocations in plastically deformed silicon.[4] The results of the present study open up some new opportunities for studying spin-dependent recombination at various defects in semiconductors.

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