The optical charge exchange $D^{\circ} \to D^{-}$ and the spin relaxation of photoelectrons in silicon

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A strong decrease at $T \lesssim 6$ K has been found in the intensity of the electron paramagetic resonance (EPR) lines of phosphorus in quenched silicon samples during optical illumination, identified as the charge exchange of $D^{\circ} \to D^{-}$. The spin relaxation (SR) rate for the conduction electrons (CE)τ_s^{-1} has been determined in the samples investigated.

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The effect of light on EPR and SR of paramagnetic centers (PC) was first studied in Si : P,[1] where it was found that $\tau_s^{-1} \approx 10^8$ sec^{-1} for a sample with a phosphorus concentration $N_p \approx 7 \times 10^{15}$ cm^{-3} at $T = 1.25$ K, and a significant decrease was observed in the EPR lines during illumination. The reason for this has remained unexplained.

In this work we studied the effect of interband optical illumination at $T = 1.8$–10 K on EPR and SR in silicon samples with $N_p = 6 \times 10^{15}(1)$, $8 \times 10^{15}(2)$ and $2 \times 10^{16}(3)$ cm^{-3}, up to and beyond thermal quenching.

An insignificant decrease in the EPR line of phosphorus was observed in the initial samples under illumination I^*/I_0 ($\sim$0.8, 0.7 and 0.6 for 1, 2, and 3, respectively), where I_0 is the EPR line intensity in darkness.

The "hole-filling" times τ_g^* were measured by a pulse-saturation technique in the EPR line and in the relaxation of the entire line τ_1^* during illumination. From the relations $\tau_1^*(\tau_g^*)^{-1} \approx 1 + N_p^* U \tau_s^{-1}$,[2] at $\tau > \tau_s$, the values $\tau_s^{-1} \approx 7 \times 10^6(1)$, $10^8(2)$, and $4 \times 10^8(3)$ sec^{-1} were found. Here U is the exchange scattering cross section,[1] and $\tau^{-1} = 10^6$–5×10^7 sec^{-1} is the CE recombination rate.

Following thermal quenching I^*/I_0 decreased substantially for samples 1–0.07 and 2–0.1, and insignificantly for 3–0.4 at $T = 4.2$ K and for the optical pumping power S_1 (Fig. 1). The temperature dependence of I^*/I_0 for sample 1 is shown in the figure for two values of S. It can be seen that I^*/I_0 decreases during a drop in T and also with an increase in S.

The decay time for the EPR signal with illumination ($\tau_{\rm dec} \approx 1$ sec) is close to the

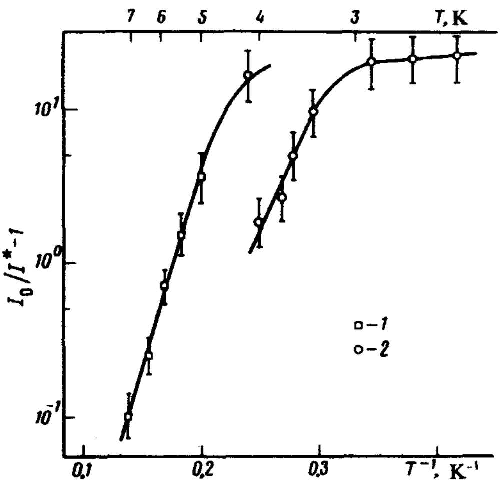

FIG. 1. Temperature variation of the EPR line intensity in a quenched sample of Si : P for interband illumination. $N_p = 6\times 10^{15}$ cm^{-3}; 1—$S_1\tau \approx 5\times 10^7$ cm^{-3}; 2—$S_2\tau \approx 1.5\times 10^7$ cm^{-3}.

time constant of an exponent, which occurs in the increase in the CE concentration n_e and has negligible weight ($\approx$0.2). Upon illumination, the signal is restored over a time of SR of phosphors in darkness τ_1.

After quenching, τ_s^{-1} increased for all the samples: $\tau_s^{-1} \approx 3\times 10^8(1)$, $3\times 10^8(2)$ and $7\times 10^8(3)$ sec^{-1}.

The EPR line decrease during illumination may be related to the heating of the spin system PC of phosphorus in the case of exchange scattering of them by spin-polarized CE,[2] and also with the charge exchange of the neutral phosphorus PC $P^0(D^0)$ to a negatively-charged centers $P^-(D^-)$ with an electron capture.[3] The charge exchange P^0–P^+ in the case of interband illumination is ineffective because of the high electron capture rate by the P^+ center.[4]

The solution of the system of kinetic equations for the CE and hole densities n_e and n_h, the neutral $N(D^0) \equiv N^*_p$ and charged phosphorus centers $N(D^-)$, the neutral $N(A^0)$ and charged $N(A^+)$ hole capture centers, concurrently with the equations for the spin-polarization relaxation of the phosphorus PC and CE in the steady-state case, leads to the following result:

$$(I^*/I_0) = K_T K_S. \qquad (1)$$

Here $K_T = [1 + RS\tau(b_-)^{-1}]^{-1}$ for $N(A^0) > N_p$; for $N(A^0) < N_p$, the minimal value is $K_T^{\min} = 1 - N(A^0)/N_P$ and $K_S^{-1} \approx 1 + \tau_s\tau^{-1}$ determine the line decrease because of the charge transfer $D^0 \to D^-(K_T)$ and spin temperature (K_S); R is the capture rate for CE by D^0, $b_- = b\exp(-E_i/kT)$ is the thermal ionization rate and E_i is the D^- center binding energy.

From a comparison of Eq. (1) with experiment, it follows that the spin temperature does not play an important role since, in order to explain I^*/I_0 as a result of K_S, it is necessary that, following quenching, τ be decreased by two orders of magnitude (for sample 2), while in actuality τ decreases by not more than a factor of three.

Consequently, the signal decay is due to the charge exchange $D^0 \to D^-$. This is also confirmed by the kinetics of the signal decay upon illumination. In the case of spin heating, the signal should fall off over a time $\tau_1^* \approx 0.1$ sec. During charge exchange the EPR signal decay and the exponent in the growth of n_e should, according to theory, have the same time constants, as observed in experiment.

When the illumination is switched off there is a rapid decay of the D^- centers[4] over a time $t \ll \tau_1$. Thus, the PC phosphorus spin system is heated up since the thermal emission of electrons occurs with an equally probable rate for both spin projections, while the thermal contact of the PC with the lattice through CE becomes ineffective because of the rapid decrease in n_e. Therefore, the EPR signal should be restored over a time τ_1, which follows from a solution of the kinetic equations and agrees with experiment.

From a comparison of Eq. (1) with experiment (Fig. 1), it was found that $E_i \approx 4$ MeV (for illumination S_1). On decreasing the illumination (S_2), E_i decreases ($E_i \approx 2.5$ MeV). These data are close to those in Ref. 3 and differ from those in Ref. 4, where it was found that $E_i = 0.78$ MeV.

Deviation from the exponent at low T (Fig. 1) and the limiting of the least possible I^*/I_0 is related to the behavior of K_T, which follows from Eq. (1) with $N(A^0) < N_p$. If $N(A^0)/N_p \ll 1$, which is apparently characteristic of the initial samples, $K_T \approx 1$ [see Eq. (1)] and the signal decay is insignificant, as is observed experimentally. An increase in the signal decay in quenched samples is related to the formation of effective capture centers for holes (e.g., dislocations[5]).

The large increase in τ_s^{-1} in the initial samples 2 and 3, following quenching, and attempts to introduce other PC into the subject samples show that the SR of CE depends on exchange scattering by PC. In initial sample 1, τ_s^{-1} is an order of magnitude smaller than that known earlier,[1] but is apparently still not the actual rate for SR of CE in silicon.

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