Ferromagnetism induced in silicon by radiation defects

A. F. Khokhlov and P. V. Pavlov

Physico-technical Research Institute of the Gor'kiĭ State University
(Submitted July 22, 1976)
Pi'ma Zh. Eksp. Teor. Fiz. **24**, No. 4, 238–240 (20 August 1976)

The presence of ferromagnetic order is established in silicon with high concentration of radiation defects.

PACS numbers: 61.80.Ki, 61.70.Kd, 76.30.Mi

It is well known that when silicon is exposed to definite doses of ions of medium energy the silicon goes over into an amorphous state. An isotropic line then appears in its ESR spectrum, with a g-factor 2.0055.[1,2] The paramagnetic radiation defects responsible for this ESR sepctrum have been named

VV centers.[2] Similar defects were observed in the amorphous silicon obtained by sputtering. Their concentration is then $N_{VV} = 2\times10^{20}$ cm^{-3}.[3] Until recently it was assumed that the maximum VV-center concentration that can be attained in silicon made amorphous by ion bombardment is also 2×10^{20} cm^{-3}. It was observed in [4], however, that when silicon is bombarded with neon ions at doses greatly exceeding the amorphization dose, N_{VV} in a thin surface layer ($\sim$100 Å) reaches 10^{21} cm^{-3}. The increase of N_{VV} at extra large doses is accompanied by a broadening of the ESR line, which is attributed to the onset of exchange interaction between the VV centers.[4] Thus, there are grounds for assuming that at low temperatures magnetic ordering is possible in silicon layers with increased concentration of paramagnetic VV centers, and this ordering leads to ferro- or anitferromagnetism. In this case the role of the unpaired electron of the d or f shell of the magnetic atoms should be played by the unpaired electron connected with the VV center.

We have used the temperature dependence of ESR in silicon bombarded by Ne^+ and Ar^+ ions at doses $(2-3)\times10^{17}$ cm^{-2}. The ion energy was 50 keV. The spectrum was recorded at 9 GHz with smooth variation of the temperature from 77 to 300 °K and with a sawtooth sweep of the magnetic field.

The figure shows the temperature dependence of the reciprocal intensity (I^{-1}) of the ESR for a sample bombarded with Ne^+ at a dose 3×10^{17} cm^{-2}. The figure shows also schematically the distribution of the VV centers.

It is seen that the high-temperature section 1 of the $I^{-1}(T)$ plot is described by the Curie-Weiss law, whereas the Curie law is satisfied on section 2. We note that an analogous $I^{-1}(T)$ dependence is obtained when silicon is bombarded with Ar^+ ions. The intensity jump at $T \approx 140$ °K is caused, in our opinion, by the following factors:

At temperatures above 140°K the contribution to the ESR is made by both

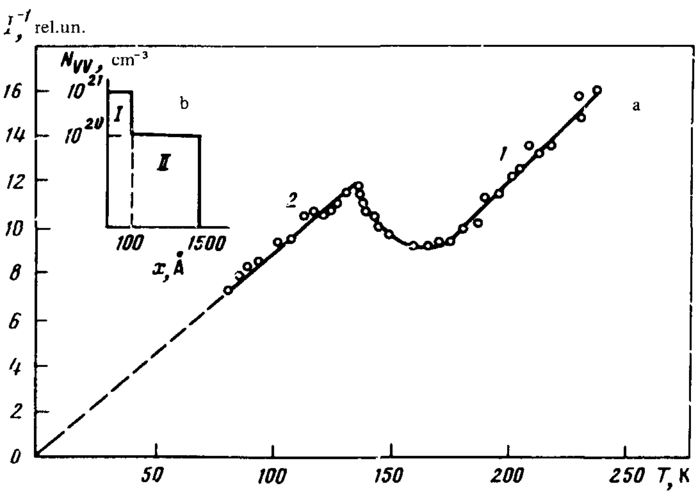

FIG. 1. Temperature dependence of the reciprocal intensity of the ESR in silicon bombarded by Ne^+ ions of energy 50 keV and dose 3×10^{17} cm^{-2} (a) and schematic representation of the profile of the defects in this sample (b).

defect layers I and II (Fig. b). Owing to the presence of exchange interaction in layer I, $I^{-1}(T)$ satisfies the Curie-Weiss law. At $T \approx 140\,°K$, magnetic ordering takes place, in layer I with the higher *VV*-center concentration, and this layer ceases to take part in the ESR. The signal intensity decreases. On section 2 of the $I^{-1}(T)$ curve the ESR intensity is determined only by layer II, where there is no order because of the low density of the paramagnetic centers. The function $I^{-1}(T)$ therefore satisfies the Curie law.

To verify finally the validity of the foregoing arguments, we have performed the following experiment. We removed layer I from a bombarded silicon sample for which the $I^{-1}(T)$ dependence was similar to that shown in the figure. We then again measured the temperature dependence of the ESR. Removal of the layer with the higher defect concentration led to the disappearance of the jump on the $I^{-1}(T)$ curve, which then agreed well with the Curie law.

The foregoing data allow us to conclude that we have observed in silicon ferromagnetism due to radiation defects. The paramagnetic Curie temperature Θ reaches 140 °K. An analysis of the data at our disposal allows us also to state that Θ changes with changing number of defects in the layer, as determined by the irradiation dose.

The question of the exchange-interaction mechanism stills calls for a solution in this case.

The authors thank E. S. Demidov, E. I. Zorin, and V. I. Pashkov for a useful discussion and A. I. Mashin for help with the measurements.

[1]B. L. Croder, R. S. Title, M. H. Brodsky, and G. D. Pettit, Appl. Phys. Lett. **16**, 205 (1970).
[2]N. N. Gerasimenko, A. V. Dvurechenskiĭ, and L. S. Smirnov, Fiz. Tekh. Poluprov. 5, 1700 (1971) [Sov. Phys. Semicond. 5, 1487 (1972)].
[3]M. H. Brodsky and R. S. Title, Phys. Rev. Lett. **23**, 581 (1968).
[4]A. F. Kokhlov, A. A. Ezhevskiĭ, E. S. Demidov, P. V. Pavlov, and E. I. Zorin, Vzaimodeĭstvie atomnykh chastits s tverdym telom (Interaction of Atomic Particles with Solids), Part 2, Khar'kov, 1976, p. 22.