# Combined resonance at dislocations in silicon

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(Submitted 16 January 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 4, 202–205 (25 February 1986)

A combined resonance corresponding to transitions between Zeeman levels of electrons trapped in a one-dimensional dislocation band has been observed in plastically deformed silicon. The electrons are trapped by virtue of their motion along a dislocation under the influence of an rf electric field.

The plastic deformation of silicon crystals gives rise to a large number of distinctive quasi-one-dimensional defects, known collectively as "dislocations," which have several interesting physical properties. They are associated with several peaks in the

0021-3640/86/040255-05$01.00

density of electron states within the band gap.[1] These peaks stem from (first) ruptured bonds at dislocation cores, which generate an ESR signal from the dislocations, (second) a pronounced distortion of the crystal around dislocation lines (the distortion has translational symmetry along the dislocation), and (third) distinctive defects which exist in and near these dislocation cores. A significant rf conductivity, observed along dislocation lines, is associated with some of these deep electron states.[2]

Annealing the deformed silicon at $T > 800\,^{\circ}\mathrm{C}$ erases the dislocation ESR signal, and the electron states due to the ruptured bonds in dislocation cores also disappear.[2] The disappearance of these ruptured bonds may be due, in particular, to a reconstruction of the dislocation cores,[3,4] with the result that the ruptured bonds are healed in pairs. Even under reconstruction conditions, however, deep quasi-one-dimensional bands may be associated with certain types of dislocations, as can be seen from the existence of an rf conductivity in $n$-type samples[2] and data on the energy spectrum.[1]

Spin-dependent effects are an interesting group of effects which can provide information on the electronic properties of dislocations in semiconductors. One of these effects, the spin-dependent recombination of electrons through ruptured bonds in dislocation cores, was studied in Ref. 5.

In addition, another spin-dependent effect has been observed in plastically deformed silicon[6] annealed at $T > 800\,^{\circ}\mathrm{C}$: a resonant change in the real ($\epsilon'$) and imaginary ($\epsilon''$) parts of the dielectric constant of the sample at the paramagnetic resonance frequency $\hbar\omega = g\mu_B H_0$. In the present letter it is our intention to show, on the basis of a study of the anisotropy of the effect, that its nature is combined spin resonance[7,8] of electrons belonging to a quasi-one-dimensional dislocation zone of one type of reconstructed dislocation.

The silicon samples studied, $n$-type ($2\times10^{14}$ P atoms/cm$^3$) and $p$-type ($10^{13}$ B atoms/cm$^3$), are plastically deformed to a 2% compression along the [110] direction at 680 °C [the dislocation density is $(2\text{–}4)\times10^{9}$ cm$^{-2}$]. After the deformation, the samples are annealed for 30 min at 850 °C. The measurements are taken at $T = 1.4$ K. A nearly spherical sample is placed in a rectangular resonator ($H_{102}$ mode) of a superheterodyne ESR spectrometer with a working frequency $f_0 \cong 9.5$ GHz. The sample is placed in a part of the resonator where the microwave electric field is $E_1 \neq 0$. In an external magnetic field $H_0 \cong 3.4$ kOe we observe a resonant change in the real and imaginary parts of the dielectric constant of the sample (Fig. 1). The amplitude of the signal, the "*Ch* line," is proportional to $E_1^2$ at a low microwave power and rapidly reaches saturation as the microwave power is raised. When the sample is moved into a region with $E_1 \cong 0$, where $H_1$ is at a maximum, the signal falls off by a factor of about 200. The $g$-factor of the *Ch* line is nearly equal to the $g$-factor of free electrons, but it has some anisotropy, varying from $g = 1.99$ to 2.016 as the sample is rotated.

The amplitude of the *Ch* line depends very strongly on the orientation of the sample with respect to the directions of $\mathbf{E}_1$ and $\mathbf{H}_0$ (Fig. 2). Analysis of the anisotropy of the amplitude $A$ as the sample is rotated around various axes show that this amplitude can be described well by

$$A = A_0 \cos^2\theta_E [1 - \sin^2\theta_H \sin^2\varphi_H], \qquad (1)$$

where the angles $\theta_E$, $\theta_H$, and $\varphi_H$ are explained in Fig. 3 (**1** and **F** are crystallographic

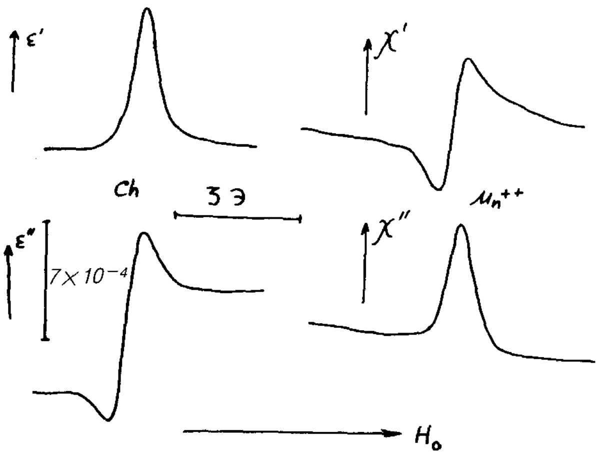

FIG. 1. Changes in the real ($\epsilon'$) and imaginary ($\epsilon''$) parts of the dielectric constant of the sample at resonance. Shown for comparison at the right is the ESR signal of a reference sample (the fourth hyperfine line of $\mathrm{Mn}^{++}$ in MgO).

directions whose meaning will become clear in the discussion below. For samples deformed by compression along the [110] or [123] direction, the directions of **1** and **F** lie within 7° of [$1\bar{1}0$] and [001), respectively. The solid curves in Fig. 2, (a) and (b), are calculated from expression (1). The anisotropy is pronounced. With $\mathbf{E}_1\|\mathbf{H}_0$, for example, the amplitude of the *Ch* line of *A* with $\mathbf{E}_1\|[110]$ is 500 times lower than that with $\mathbf{E}_1\|[1\bar{1}0]$!

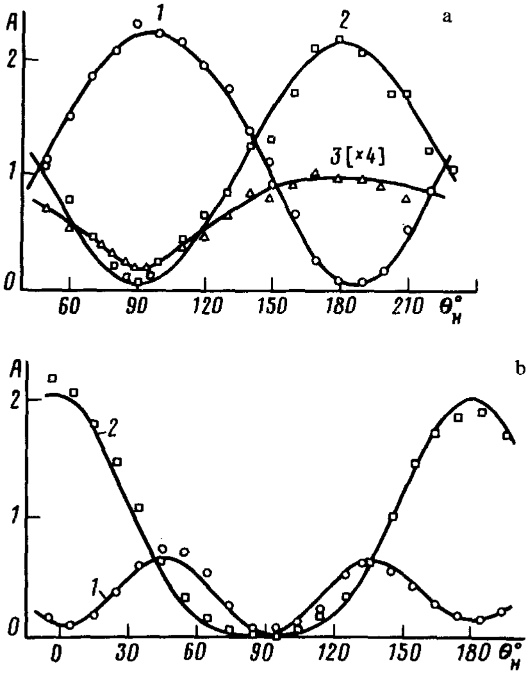

FIG. 2. Anisotropy of the amplitude of the *Ch* line as the sample is rotated around $\vec{\Omega}$. Microwave power: $P=1.5\times10^{-7}$ W for 1 and 2; $P=1.6\times10^{-4}$ W for 3. Curves 1—$\mathbf{E}_1\perp\mathbf{H}_0(\theta_E=\theta_H+\pi/2)$; curves 2 and 3—$\mathbf{E}_1\|\mathbf{H}_0(\theta_E=\theta_H)$. (a) Dependence on the angle between $\mathbf{H}_0$ and the [$1\bar{1}0$] axis, $\vec{\Omega}=[110]$ ($\varphi_H=0$). (b) The same, but with $\vec{\Omega}=[001]$ ($\varphi_H=\pi/2$).

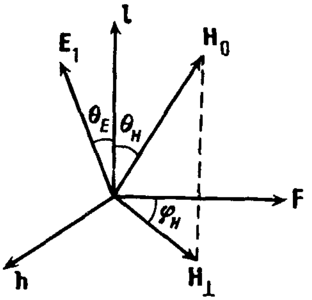

FIG. 3. **1**—Direction of the dislocation axis ([110]); **F**—direction of the crystal field ([001]); $\tilde{\mathbf{h}}$—direction of the effective microwave magnetic field ([110]); $\mathbf{H}_0$—static magnetic field; $\theta_H$ and $\varphi_H$—polar and azimuthal angles of $\mathbf{H}_0$; $\mathbf{E}_1$—microwave electric field; $\theta_E$—polar angle of $\mathbf{E}_1$.

This unusually pronounced anisotropy of the effect and also the fact that the effect is far stronger than the ordinary ESR effect suggest that the effect is a consequence of a combined resonance in a quasi-one-dimensional system. The spectrum of electrons in a band associated with a dislocation having an edge component is formed by the potential of the core, which has a low symmetry; i.e., an electron is subjected to a crystal field **F** which is directed perpendicular to the dislocation axis, **1**. The motion of the electrons along **1** at a velocity **v** gives rise, through a relativistic effect, to a magnetic field $\tilde{\mathbf{h}} = -[\mathbf{v}\times\mathbf{F}]/ec$, which directly affects the spin. In an external field $\mathbf{E}_1(\omega)$, the velocity **v** acquires an rf component, which leads to transitions between Zeeman sublevels (the combined resonance predicted by Rashba[7,8]). The intensity of the combined resonance for band electrons is considerably higher than the ESR intensity. It can be shown that in this case the behavior of the intensity of the combined resonance as a function of the orientation of the static magnetic field $\mathbf{H}_0$ and of the microwave field $\mathbf{E}_1$ is described by expression (1).

The observation of a combined resonance leads to certain conclusions regarding the nature of the spectrum of the electrons that are involved in the resonance, the symmetry of the crystal field at the core, and the magnitude of this field. The fact that the combined-resonance signal is much stronger than the ESR signal is clearly evidence that the electron states are of a band nature. According to data on the orientation dependence of the *Ch* line, this band is one-dimensional; i.e., the combined resonance is excited exclusively by the component of $\mathbf{E}_1$ parallel to the dislocation axis. The intensity of the combined resonance is determined by the magnitude of the field **F** which arises from the lowering of the symmetry in the dislocation core. We can find an estimate by comparing the intensities of the combined resonance and the ESR:

$$A_{CR}/A_{\mathrm{ESR}} \cong (\tilde{h}/H_1)^2 \cong (E_1/H_1)^2\,(F/mc\omega)^2 .$$

Since we have $A_{CR}/A_{\mathrm{ESR}} \gtrsim 200$, and since we have $E_1 \cong H_1/3$ under these experimental conditions, we find $F/e \gtrsim 5\times10^7$ V/cm. This large value of $F$ indicates that the electron band responsible for the combined resonance corresponds to deep states in the band gap of the semiconductor.

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Translated by Dave Parsons