Semiconductor Physics, Quantum Electronics & Optoelectronics. 2000. V. 3, N 4. P. 449-452.

PACS: 61.72.T, 72.20.M

The features of magnetoresistance of *n*-Si doped with phosphorus from the melt and by nuclear transmutation

P.I. Baranskii, V.M. Babich, E.F. Venger, Yu.P. Dotsenko

Institute of Semiconductor Physics, NAS Ukraine, 45 Prospect Nauki, Kyiv, 03028, Ukraine
Tel.: (380-44) 265-62-80; Fax: (380-44) 265-83-42; E-mail: jornal@isp.kiev.ua

Abstract. The magnetic field dependencies $\Delta\rho_\perp/\rho_0 = f(H)$ were investigated for phosphorus-doped *n*-Si crystals at a temperature of 77.4 K in classical strong magnetic fields up to 200 kOe. We revealed and discuss some distinctions in the field dependencies of magnetoresistance for crystals doped from melt and those doped by nuclear transmutation. It is shown that magnetoresistance $\Delta\rho_\perp/\rho_0$ in classical strong magnetic fields is due to the statistically distributed Herring-type defects in the crystals studied.

Keywords: magnetoresistance, classical strong magnetic field, impurity, nuclear transmutation.

Paper received 05.06.00; revised manuscript received 07.11.00; accepted for publication 12.12.00.

1. Introduction

In [1] the authors have analyzed the effect of «growth layers» on magnetoresistance for *n*-Si when magnetic field H was oriented perpendicular to the current J ($\vec{H} \perp \vec{J}$). The role of heat treatment in formation of both magnetoresistance (also in the case $\vec{H} \parallel \vec{J}$) and longitudinal piezoresistance in the above crystals was determined in [2]. The results obtained in [1, 2] made prerequisites for more profound investigation of the magnetic field dependencies of transverse magnetoresistance, $\Delta\rho_\perp/\rho_0 = f(H)$, over a wide range of magnetic field strength in *n*-Si doped with phosphorus. Doping was made in two ways: from the melt [3] or by nuclear transmutation [4, 5].

Our objective was to elucidate what reasons, as a rule, exclude flattening out for the function $\Delta\rho_\perp/\rho_0 = f(H)$ in the region of classical strong magnetic fields (CSMF), i.e., those meeting the requirement $\mu H/c >> 1$ (here μ is the charge carrier mobility).

2. Experimental procedure

Our experiments have been carried out at a temperature of 77.4 K in pulse magnetic fields ($0 \le H \le 200$ kOe) for *n*-Si:P single crystals. The samples studied were doped with phosphorus either from the melt (*n*-Si:<M>) or using nuclear transmutation (*n*-Si:<NT>). Their crystallographic orientation and electrophysical parameters are given in Table 1.

It should be noted that even for the sample with the lowest charge carrier mobility ($\mu_{77.4\,K} = 15000$ cm^2/V·s) the CSMF criterion corresponded to the value $\mu H/c = 7.5 > 1$ starting from $H = 50$ kOe. At $H = 200$ kOe this ratio was $\mu H/c \approx 30 >> 1$.

In what follows α will denote the angle between the crystal growth direction (i.e., the normal $\vec{N}$ to growth layers) and current direction $\vec{J}$.

3. Results and discussion

The results of our experiments have shown that magnetoresistance observed by us intensely grew without flattening out (i.e., behaved contrary to the classical theory) - see Figs. 1 and 2. (This occurred not only at $\alpha = 72°$, but even at $\alpha = 90°$. According to [1, 6], at the latter value the effect of growth layers on the effective magnetoresistance $\Delta\rho_\perp/\rho_0$ formation in CSMF is completely excluded.) The experimental curves presented in both figures were obtained with measured signals sweeping by magnetic field. The curves 1 and 2 were taken at $\alpha = 0°$ (this corresponds to the maximally possible manifestation of growth layers), while the curves 1′ and 2′ were taken at $\alpha = 90°$ (as was mentioned earlier, in this case the effect of growth layers is practically excluded, even if they are present in the crystal studied).

The observed magnetoresistance changing in the region of expected saturation might be due to the following effects:

Table 1. Electrophysical parameters and crystallographic orientations of the studied *n*-Si crystals (doped with phosphorus) (T = 77.4 K).

Sample number	Method of doping	Crystal growth orientation	Electron concentration n_e, 10^{13} cm^{-3}	Electron mobility μ, cm^2/V·s	Orientation of		Minimal values of quantizing magnetic field H, kOe
					current J	magnetic field H	
1	<M>	<100>	24	15000	<110>	<100>	108
2	<NT>	<111>	25	17800	<110>	<100>	108
3	<M>	<111>	1.7	19300	<110>	<100>	108
4	<NT>	<111>	1.9	20000	<110>	<100>	108
5	<M>	<100>	10	18200	<111>	<110>	139
6	<NT>	<100>	11.3	18850	<111>	<110>	139

1/ quantization (especially as for *n*-Ge $\Delta\rho_\perp/\rho_0 \sim H$ or, in some cases, $\sim H^2$; these dependencies have been experimentally determined and got theoretical substantiation in [7] for the case of quantizing magnetic fields);

2/ growth layers «bending», taking into account that the crystallization front (and consequently the growth layers) cannot be absolutely flat;

3/ randomly distributed Herring-type nonuniformities [8] of substantially different nature [9];

4/ charge carrier scattering from oriented (ordered) dislocation [10].

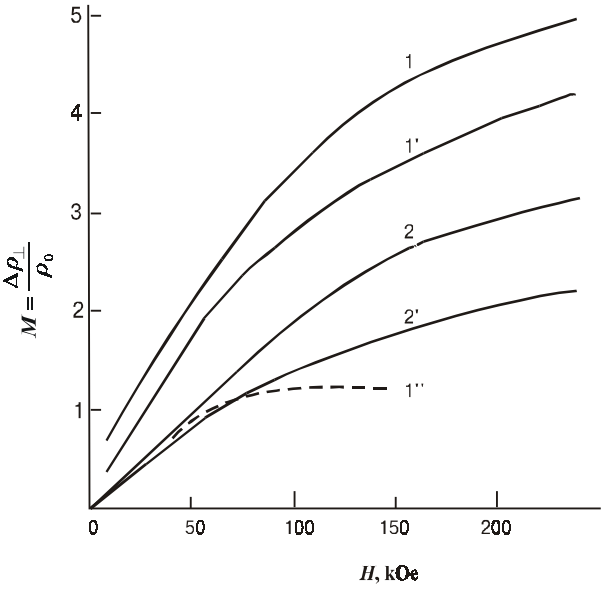

Fig. 1. $\Delta\rho_\perp/\rho_0 = f(H)$ curves taken at T = 77.4 K for the samples 1 and 2 (curves 2 and 2′) and 3 and 4 (curves 1 and 1′). Curves 1 and 2 (1′ and 2′) were taken for the samples doped with phosphorus from the melt (by nuclear transmutation). The dashed curve 1″ was calculated using the theory of anisotropic scattering (for $n_e = N_I = 1.7\cdot10^{13}$ cm^{-3} and T = 77.4 K) without accounting for quantization effects.

Our samples were practically dislocation-free; so the fourth of the above effects should be excluded from consideration. Let us now analyze the rest three effects (1 to3) in more detail.

For both *n*-Si and *n*-Ge one can easily determine the lower bound for quantizing magnetic fields H oriented along the principal crystallographic axes. For this one should apply the well-known quantization criterion (at a temperature of our experiments, 77.4 K) and use the expression for cyclotron effective mass m_c^*:

$$m_c^* = \left[\frac{m_\parallel m_\perp^2}{m_\parallel \cos^2\theta + m_\perp \sin^2\theta}\right]^{1/2} \equiv m_1^* (\text{or } m_2^*) .$$

Here θ is the angle between H and longitudinal axis of the isoenergy ellipsoid; $m_{||}$ and $m_\perp$ are, correspondingly, the electron longitudinal and transverse effective masses whose values for *n*-Si and *n*-Ge are well known.

The minimal values of quantizing magnetic fields H are given in Table 2. One can see that in *n*-Si, even under the most favorable conditions, the quantization effects begin to manifest themselves in magnetic fields $H \geq 110 \div 140$ kOe only. (This situation differs from that in *n*-Ge where, at 77.4 K, the quantization may begin in magnetic fields of 50÷60 kOe for some cyclotron effective masses.) One can see from comparison of the curves 1′ and 1″ (Fig. 1) that even at 100 kOe the ratio between magnetoresistance (that characterizes the above curves) $\beta \equiv M(1')/M(1'')|_{100\ \text{kOe}} = 2.46$. Therefore, at magnetic fields used by us, the quantization effect cannot be decisive in formation of the curves presented in Figs 1, 2.

To evaluate the role of growth layer «bending» in magnetoresistance formation in CSMF, we used the samples 5 and 6. They provided the possibility to perform experiments at maximally possible growth layer manifestation (i.e., at $\alpha = 0°$ — see curves 1 and 2 in Fig. 2), as well as at $\alpha = 90°$. In the latter case, according to [1], the growth layer effect on $\Delta\rho_\perp/\rho_0$ formation is practically completely excluded for crystals grown in the direction <100> — see curves 1′ and 2′ in Fig. 2.

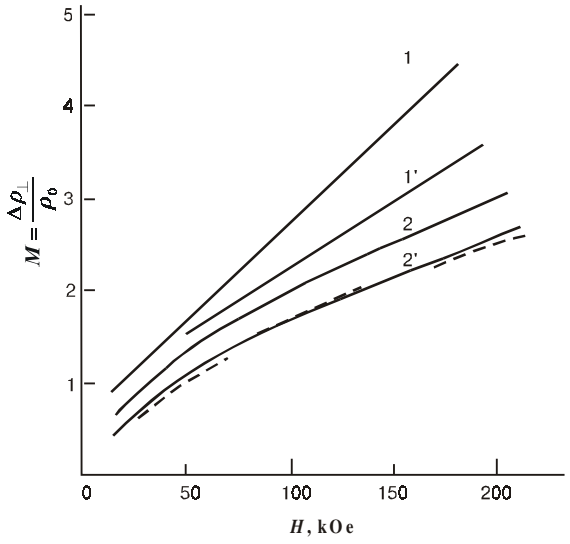

Fig. 2. $\Delta\rho_\perp/\rho_0 = f(H)$ curves taken at T = 77.4 K for the samples 5 (curves 1 and 1′) and 6 (curves 2 and 2′).

For crystal 5 doped from the melt, the well-formed growth layers led to an increase in $M(1)$ value, as compared to that of $M(1')$, by not over than 20%, even under the most favorable conditions — at $\alpha = 0°$ and magnetic field as high as 200 kOe. So a small component of this effect (due to growth layers «buckling» when performing measurements at $\alpha = 90°$) in no way could result in the $\Delta\rho_\perp/\rho_0$ value departure from the expected saturation (somewhere in the 50÷60 kOe region) by a factor of more than 2.5÷3. Therefore this effect (growth layers «bending») cannot be considered as being responsible for $\Delta\rho_\perp/\rho_0$ value increase in CSMF.

From the above analysis it follows that for *n*-Si the most probable reason for $\Delta\rho_\perp/\rho_0$ formation in the CSMF region lies in randomly distributed Herring-type nonuniformities (see item 3/ above). This conclusion is also supported by the fact that the slope of curve 2′ (being transferred from Fig. 1 to Fig. 2, with some shift along the axis of ordinates) is almost the same as that of curve 2′ in Fig. 2 — see dotted line in Fig. 2. This is true, even though the crystals used in experiments to take both above curves differed in the charge carrier concentration n_e by a factor of almost 2.5 and were grown along the different crystallographic directions (<111> and <100>). In addition, both J and H were differently oriented in experiments with these crystals: $J \parallel$ <110> and $H \parallel$ <001> (for curve 2′, Fig. 1), $J \parallel$ <111> and $H \parallel$ <110> (for curve 2′, Fig. 2).

The only fact in common for the above two crystals (2 and 6, Table 1) was the method of doping (nuclear transmutation). This fact does not seem to be of no importance in formation of the nonuniformities proper, as well as their structure. Manifestation of just this fact is that for both pairs of samples (whose mean charge carrier concentrations n_e were very close) higher $\Delta\rho_\perp/\rho_0$ values were observed for *n*-Si<M> (i.e., doped with phosphorus from the melt) – see curves 1 and 2, Fig. 1, rather than *n*-Si <NT> – see curves 1′ and 2′, Fig. 1. This conclusion is also supported by the experimental results obtained under conditions of maximal, as well as minimal, growth layer manifestation – curves 1, 2 and 1′, 2′, respectively, in Fig. 2.

Table 2. Minimal quantizing magnetic field values (in kOe) for *n*-type Si and Ge at different crystallographic orientations of H (T = 77.4 K).

Sample	Parameters							
	$m_\parallel/m_0$	$m_\perp/m_0$	Orientation of magnetic field					
			$H \parallel$ <110>		$H \parallel$ <100>		$H \parallel$ <111>	
n-Si	0.91	0.191	θ_1	90°	θ_1	90°	θ	54°45′
			m_1^*	$0.417m_0$	m_1^*	$0.417m_0$		
			H_1	236	H_1	236	m^*	$0.278m_0$
			θ_2	45°	θ_2	0°		
			m_2^*	$0.245m_0$	m_2^*	$0.191m_0$	H	158
			H_2	139	H_2	108		
n-Ge	1.58	0.082	θ_1	90°	θ	54°45′	θ_1	0°
			m_1^*	$0.36m_0$			m_1^*	$0.082m_0$
			H_1	202	m^*	$0.135m_0$	H_1	46
			θ_2	35°12′			θ_2	70°30′
			m_2^*	$0.1m_0$	H	76	m_2^*	$0.207m_0$
			H_2	57			H_2	116

Concluding remarks

Thus, when one deals with the level of magnetoresistance formation in CSMF (as in problems related to the charge carrier mobility formation), *n*-Si<NT> crystals (i.e., those doped with phosphorus using nuclear transmutation) may be considered as being more perfect than *n*-Si<M> crystals (i.e., doped with phosphorus from the melt). The reason for this lies predominantly in different temperature conditions of impurity atoms introduction into the crystal lattice.

One should remember, however, that a transition might occur from the situation when the defect sizes are comparable to the de Broglie wavelength for an electron in crystal lattice to that when the defect sizes become comparable to the maximal wavelength of phonons. In this case the above conclusion may give way to the opposite one, as is known from [11, 12]. This remark, however, concerns mainly the kinetic effects dealing with phonon motion and scattering mechanisms. Such problems lie beyond the scope of this work, and so they are not considered here.

References

1. P.I. Baranskii, V.M. Babich, Yu.P. Dotsenko et al., Effect of growth layers and statistically distributed nonuniformities on magnetoresistance of *n*-Si (in Russian) // *Fiz. Tekhn. Poluprov*. **13**(6), pp. 1216-1219 (1979).
2. P.I. Baranskii, V.M. Babich, Yu.P. Dotsenko et al., Effect of heat treatment on the electrophysical properties of normal and nuclear-transmutation-doped silicon crystals (in Russian) // *Fiz. Tekhn. Poluprov*. **14**(8), pp. 1546-1549 (1980).
3. I.V. Salli, E.S. Falkevich, *Production of Semiconducting Silicon* (in Russian), Metallurgiya, Moscow (1970).
4. W.E. Haas, M. Schnöller, Silicon doping by nuclear transmutation // *J. Electron. Mater*. **5**(1), pp. 57-68 (1976).
5. L.S. Smirnov, S.P. Soloviev, V.F. Stas', V.A. Kharchenko, *Nuclear Transmutation Doping of Semiconductors* (in Russian), Nauka, Novosibirsk.
6. P.I. Baranskii, V.M. Babich, Layered crystal structure and transverse magnetoresistance of *n*-germanium in strong magnetic fields (in Russian) // *Fiz. Tekhn. Poluprov*. **3**(5), pp. 689-696 (1969).
7. V.M. Babich, P.I. Baranskii, A.G. Samoilovich et al., Transverse magnetoresistance of *n*-type Ge in quantizing magnetic fields // *phys. stat. sol. (b)* **55**, pp.457-466 (1973).
8. C. Herring, Effect of random inhomogeneities on electrical and Galvanomagnetic Measurments // *J. Appl. Phys.* **31**(11), pp. 1939-1953 (1960).
9. V.M. Babich, P.I. Baranskii, O.P. Gorodnichii, On a problem of magnetoresistance nature in *n*- and *p*-InSb (in Ukrainian) // *Ukr. Fiz. Zhurn*. **15**(11), pp. 1918-1921 (1971).
10. P.I. Baranskii, M.M. Vishnevskii, O.P. Gorodnichii, Magnetoresistance and Hall effect in *n*-InSb single crystals with high dislocation density (in Ukrainian) // *Ukr. Fiz. Zhurn*. **13**(7), pp. 1099-1103 (1968).
11. P.I. Baranskii, V.V. Savyak, L.A. Scherbina, Study of the phonon-phonon relaxation in nuclear-transmutation-doped and normal silicon crystals (in Russian) // *Fiz. Tekhn. Poluprov*. **14**(2), pp. 302-305 (1980).
12. P.I. Baranskii, V.V. Savyak, Yu.V. Simonenko, Effect of heat treatment conditions on the dragging piezo-thermoelectric voltage in nuclear-transmutation-doped and normal silicon crystals (in Russian) // *Fiz. Tekhn. Poluprov*. **19**(9), pp. 1712-1715 (1985).