Heating effects and electron-phonon interaction in a two-dimensional hole gas

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A study was made of the effects of heating of two-dimensional holes near the (100), (110), and (111) surfaces of silicon by measuring the anomalous magnetoresistance. An investigation was made of the energy relaxation time of holes τ_ε, scattered by phonons, as a function of the lattice temperature and of the carrier density. The observed features of the heating effects were attributed to filling of the second quantum subband.

1. INTRODUCTION

The electron-phonon interaction in two-dimensional systems near the surface of a semiconductor has been investigated intensively for over a decade not only because of the fundamental nature and importance of this type of interaction, but also because it is not yet fully understood.[1] One of the methods for investigating this interaction involves a study of the effects of carrier heating by a longitudinal electric field applied along the surface of a semiconductor. The published heating experiments have been devoted mostly to a two-dimensional ($2D$) electron gas.[2–8] Much less work has been done on a $2D$ hole gas, although studies of the heating effects and, consequently, of the interaction of phonons in the hole system are undoubtedly desirable because the energy spectrum of $2D$ holes has a number of special features. In particular, a situation when two size-quantization subbands are filled simultaneously is frequently encountered[1] in the hole subsystem and this may affect the nature of the electron-phonon interaction. The published literature on the heating effects in hole inversion channels is limited to two reports,[3,9] but because of the poor quality of the samples and the complexity of the method employed (involving the use of quantizing magnetic fields up to 100 kG) the information on the interaction of $2D$ holes with phonons obtained in this way is fragmented and incomplete.

A new impetus for these investigations was provided by the discovery of an anomalous magnetoresistance (AMR)[10,11] which has now become an effective method for investigating electron processes in disordered Fermi systems.[12] It is known that the AMR amplitude obtained in the presence of a fixed magnetic field is determined by the relaxation time τ_φ of the wave-function phase.[10,13] There have been many investigations (see Ref. 12) of the AMR of $2D$ electron systems and it has been found that the relaxation time τ_φ is determined by inelastic collisions of carriers with one another and is governed by the temperature of the $2D$ gas. Therefore, the relaxation time τ_φ and, consequently, the AMR provide a measure of the electron temperature and changes in these quantities can be used to determine this temperature. An important advantage of this method for the determination of the electron temperature, compared with traditional measurements of the amplitude of the Shubnikov-de Haas oscillations, in heating electric fields is the use of weaker magnetic fields, which in contrast to the quantizing fields, do not affect the energy spectrum of carriers and, consequently, do not alter the electron-phonon interaction.

We compared the temperature and field dependences of the AMR to find the temperature of $2D$ holes at the surface of silicon as a function of the applied electric field. This was used to find the energy relaxation time of holes when they were scattered by phonons. Certain special features of the heating effects due to the filling of two quantum subbands were observed.

2. DETERMINATION OF THE TEMPERATURE OF 2D HOLES FROM THE ANOMALOUS MAGNETORESISTANCE CHARACTERISTICS DURING HEATING IN AN ELECTRIC FIELD

We determined the magnetoconductance $\Delta G(H) = G(H) - G(0)$ of inversion p-type channels in magnetic fields H up to 3 kG at temperatures in the range 1.6–4.2 K using longitudinal electric fields E_{SD} up to 5 V/cm. The measurement method was described earlier.[14,15] Nonlinear effects of nonthermal origin, which could affect the conductance and the results of our measurements, were exhibited in our samples only at low hole densities p_s

TABLE I. Parameters of investigated samples.

Group No.	Orientation	$N_{D,A}$, 10^{15} cm^{-3}	μ, cm^2 $\cdot$V$^{-1}\cdot$sec^{-1}	L, μ	L/W	d, Å
1	(100)	0.2	1500	1200	3	1500
2	(100)	1	800	750	3	1200
3*	(100)	5	1500	1800	3.6	1000
4	(111)	0.5	1100	1200	3	1300
5	(111)	0.1	1400	1200	3	1650
6	(110)	0.25	2500	1200	3	1100

Note. Here, $N_{D,A}$ are the donor and acceptor dopant concentrations; μ is the maximum mobility of holes in a channel at 4.2 K; L and W are the length and width of the channel; d is the thickness of the oxide.
*This denotes inversion channels in MIS-SOS structures.

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$\lesssim 7\times 10^{11}$ cm^{-2}. The measurements were carried out in the range of densities $(1.5–6)\times 10^{12}$ cm^{-2}. Possible contact effects were avoided by the use of potentiometric probes. The parameters and orientation of the surface of the investigated samples are given in Table I. It should be pointed out that the results obtained for samples with different and identical parameters were practically the same provided the orientation of the surface was the same, irrespective of the technology used in the fabrication of the samples, apart from the structures of silicon on sapphire, which will be discussed separately. It had been established earlier[15] that the AMR of a $2D$ hole gas in silicon was positive for all the main orientations of the surface and could be described fully by a theory of quantum corrections to the conductance subject to an allowance for the spin-orbit interaction.[10] In this case, we can use

$$\Delta G(H) = -\frac{e^2}{2\pi^2\hbar}\left[-\frac{3}{2}f(x^*) + \frac{1}{2}f(x)\right], \tag{1}$$

where

$$x = \frac{4DeH}{\hbar c}\tau_\varphi, \quad x^* = \frac{4DeH}{\hbar c}\tau_\varphi^*;$$

$$(\tau_\varphi^*)^{-1} = \tau_\varphi^{-1} + {}^4\!/_3\tau_{so}^{-1}, \quad f(x) = \ln x + \psi({}^1\!/_2 + 1/x);$$

$\psi(y)$ is the logarithmic derivative of the gamma function; D is the diffusion coefficient; τ_{so} is the spin relaxation time. It was found that the spin relaxation mechanisms were the scattering due to lifting of the spin degeneracy in a noncentrosymmetric system and, in the case of filling of two quantum subbands, the scattering between the heavy- and light-hole bands. Relaxation of the wave-function phase was determined by inelastic collisions of holes with one another subject to an allowance for their scattering on static defects. The temperature dependence of $\Delta G(H)$ was governed by the dependence of the relaxation time τ_φ on T_L, since τ_{so} did not vary with temperature.

By way of example, we shall consider now the dependence of the magnetoconductance on the applied magnetic field in the presence of a small longitudinal current when the lattice temperature T_L was varied (Fig. 1a) and also at a fixed lattice temperature but for different values of the field E_{SD} (Fig. 1b) applied to one of the samples of the fourth group with the (111) surface orientation. Clearly, $|\Delta G(H)|$ increased on reduction in temperature and in the longitudinal electric field. We also included in this figure the dependences $\Delta G(H)$ calculated from Eq. (1) employing the parameters given in the caption of this figure. In all cases the theoretical curves agreed well with the experimental results and an increase in $|\Delta G(H)|$ as a result of cooling was due to an increase in τ_φ, similar to that reported in Ref. 15. The values of τ_φ and τ_{so} obtained for different longitudinal electric fields could also be deduced from a comparison of the corresponding experimental and theoretical curves. This comparison indicated that the agreement betweeen the theoretical and experimental dependences remained good on increase in E_{SD}; this reduced τ_φ, whereas the time τ_{so} remained unchanged. This behavior of the AMR was explained by the heating of a hole $2D$ gas in a longitudinal electric field. The power transferred to the hole subsystem increased the energy of thermal motion of carriers; it was then transferred to the lattice by the electron-phonon interaction. A temperature T_h exceeding the lattice temperature

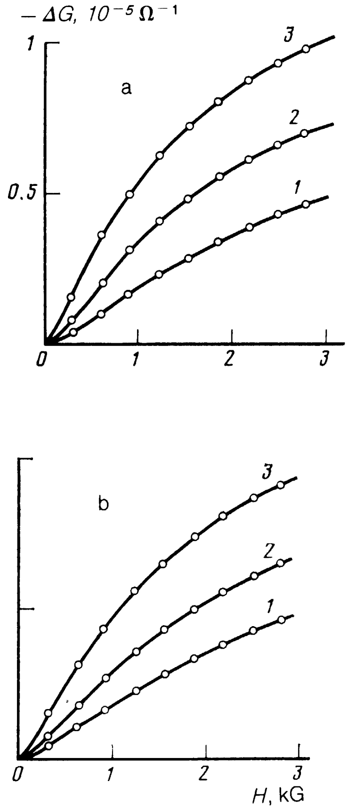

FIG. 1. Dependences of the magnetoconductance ΔG of an inversion channel on the (111) surface of Si (sample belonging to group No. 4) on the magnetic field ($p_s = 3.8\times 10^{12}$ cm^{-2}, $D = 11.6$ cm^2/sec). a) T_L (K): 1) 4.2, 2) 2.8, 3) 1.9; $E_{SD} = 0.18$ V/cm. b) E_{SD} (V/cm): 1) 5.2, 2) 2.1, 3) 0.75; $T_L = 1.7$ K. The points are the experimental results and the continuous curves are calculated using Eq. (1) employing the parameters $\tau_{so} = 0.65\times 10^{-12}$ sec and assuming that: a) $\tau_\varphi = 5.6$, 9.7, and 16.7×10^{-12} sec (curves 1, 2, and 3, respectively); b) $\tau_\varphi = 5.6$, 7.5, and 14.4×10^{-12} sec (curves 1, 2, and 3, respectively).

was established inside the hole subsystem, because the electron-electron collision time $\tau_{ee}\propto\tau_\varphi$ was much less than the energy relaxation time τ_ε governed by the scattering on phonons. It should be pointed out that the heating of the lattice subsystem was negligible (it is estimated that it amounted to $\Delta T_L \approx 1.01$ K when $\Delta T_h = T_h - T_L \approx 1$ K). An increase in T_h increased the frequency of collisions of holes with one another and this reduced τ_φ and, consequently, also $|\Delta G(H)|$, as confirmed experimentally. A comparison of the temperature and field dependences of $\Delta G(H)$ (Fig. 1) yielded the temperature of the hole subsystem for different values of the power $P = GE_{SD}^2$ delivered by the electric field to the system. Figure 2 shows the $T_h(P)$ dependence obtained for samples with the (111) and (100) orientations. Clearly, up to $P = 5\times 10^{-5}$ W/cm^2 the temperature T_h of $2D$ holes at the (111) surface was not affected significantly and then it began to rise in accordance with the law $(T_h^5 - T_L^5)\propto P$. For $2D$ holes at the (100) surface the heating began (Fig. 2) at higher pump powers, although the mobility, effective masses, and carrier densities were practically the same for these orientations.

The heating effects were also investigated in the case of $2D$ holes in channels of metal-insulator-semiconductor (MIS) transistors made from silicon-on-sapphire (SOS)

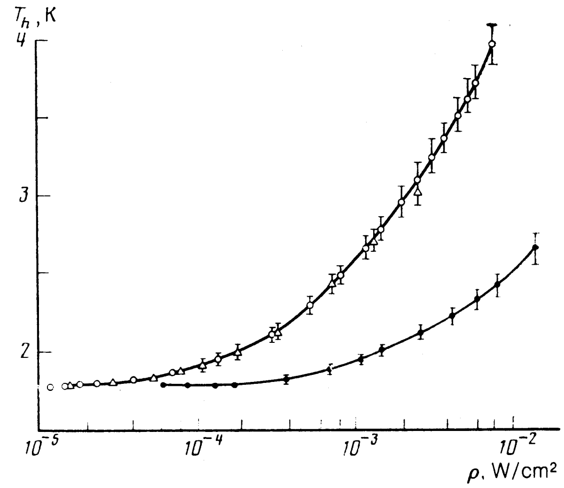

FIG. 2. Dependences of the temperature of a two-dimensional hole gas on the pump power ($T_L = 1.7$ K). Samples belonging to different groups: ○) No. 4, ●) No. 1; △) No. 3; $p_s = 3.6\times10^{12}$ cm^{-2}.

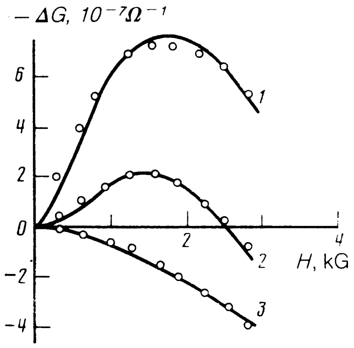

FIG. 3. Dependences of $\Delta G(H)$ for an inversion channel on the (100) surface of Si in MIS-SOS structures (sample of group No. 3, $T = 1.7$ K, $p_s = 1.6\times10^{12}$ cm^{-2}, $D = 5.2$ cm²/sec) obtained in different electric fields E_{SD} (V/cm): 1) 0.42; 2) 1.62; 3) 7.4. The points are the experimental values and the continuous curves are calculated using Eq. (1) and assuming the following values τ_φ (10^{-12} sec): 1) 9.3; 2) 6.3; 3) 1.6; $\tau_{so} = 6.2\times10^{-12}$ sec.

films when the Si orientation was (100); a special feature of transistor structures was a compressive strain which increased the energy gap between the light- and heavy-hole subbands. Before beginning our analysis of the dependences of $\Delta G(H)$ on T_L and E_{SD} in the case of MIS-SOS structures, we shall discuss some characteristics of the AMR in this case. It had been established[14,15] that the AMR of these structures had a variable sign, in contrast to inversion channels in undeformed silicon when the AMR was always positive. It was found that when the AMR was positive (in the range of magnetic fields used in these experiments), the inequality $\tau_\varphi > \tau_{so}$ was satisfied, but cooling (i.e., reduction of τ_φ) reversed this inequality and this reversed the sign of the magnetoresistance. Application of heating electric fields also increased the temperature of the system. Therefore, in low longitudinal electric fields the values of $\Delta G(H)$ were negative, but on increase in E_{SD} the sign of the magnetoresistance was reversed. This is illustrated in Fig. 3, which gives the dependences $\Delta G(H)$ for an MIS-SOS structure subjected to different longitudinal electric fields. Clearly, an increase in E_{SD} reversed the sign of the magnetoconductance from negative to positive and the theoretical curves agreed well with the experimental results for the values of τ_φ and τ_{so} given above. An increase in E_{SD} did not affect the value of τ_{so}, but it reduced τ_φ, corresponding to an increase in the temperature of $2D$ holes. A comparison of the temperature and field dependences of the AMR yielded the dependence of the temperature of the hole subsystem on the pump power, shown in Fig. 2. This dependence was clearly identical with the dependence $T_h(P)$ for $2D$ holes at the (111) surface.

3. ENERGY RELAXATION TIME OF 2D HOLES SCATTERED BY PHONONS

Heating in an electric field is characterized by an energy relaxation time τ_ε determined from the balance of the energy received by carriers from the field and of the energy transferred from the carriers to the phonon subsystem on condition that $\Delta T_h \ll T_L$ (Ref. 16):

$$P=C(T)(T_h-T_L)/\tau_\varepsilon=\pi^2k^2T(T_h-T_L)N/3\tau_\varepsilon, \qquad (2)$$

where $N = m_p^*/\pi\hbar^2$ is the density of states at the Fermi level and m_p^* is the effective mass of holes, which is equal to the mass of heavy holes m_h^* in the case of filling of one quantum subband and $m_p^* = m_h^* + m_l^*$ (m_l^* is the mass of a light hole) in the case of filling of two quantum subbands. It should be noted that Eq. (2) is valid only in the case of a weak parabolicity of the dispersion law of carriers $[(dN/d\varepsilon)_{\varepsilon_F}\varepsilon_F \ll N]$. This situation is encountered in $2D$ hole gas in the range of densities $p_s \gtrsim 1.5\times10^{12}$ cm^{-2} under consideration.[1]

The initial part of the dependence $T_h(P)$ and the relationship (2) can be used to find the relaxation time τ_ε. In our case this initial region is limited by the condition $\Delta T_h/T_L \lesssim 15\%$. The results obtained for all the investigated silicon surface orientations are presented below. Figure 4a gives the dependence $\tau_\varepsilon(p_s)$ for $2D$ holes near the (111) surface. Clearly, τ_ε decreased on increase in p_s in accordance with a near-linear law. It is clear from Fig. 4b that in the case of the hole $2D$ gas at the (100) surface the time τ_ε behaved differently: in the case of undeformed structures (curve 2) the relaxation time was, firstly, several times smaller than the value of τ_ε for holes at the (111) surface and, secondly, it

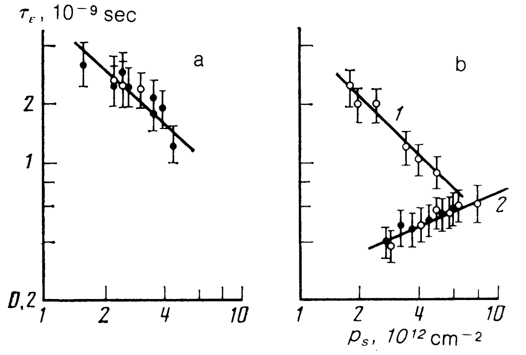

FIG. 4. Dependences of the energy relaxation time τ_ε on p_s for samples with different orientations of the surface ($T_L = 1.7$ K): a) sample with the (111) orientation (the black points represent group No. 4 and the open circles represent group No. 5); b) sample with the (100) orientation [line 1 represents group No. 3, whereas line 2 represents group No. 1 (black points) or group No. 2 (open circles)].

increased on increase in the density in accordance with the law $\tau_\varepsilon \propto p_s^\alpha$, where $\alpha = 0.5 \pm 0.4$. In the case of MIS-SOS structures (curve 1) the behavior of τ_ε was practically identical with the behavior of the energy relaxation time of holes at the (111) surface. In the case of holes at the (110) surface of Si we determined the value of $\Delta T_h/P$ because in the case of this system the filling of the second quantum subband began in the range of densities $p_s = (2\text{–}3)\times 10^{12}$ cm^{-2}. This did not allow us to determine τ_ε from Eq. (2), because at the moment of transition there was an abrupt change in the density of states at the Fermi level.

Figure 5 shows the dependence of $\Delta T_h/P$ on p_s for holes near the (110) surface. Clearly, in the density range $(1.5\text{–}2.5)\times 10^{12}$ cm^{-2} there was first a slight change and then a rapid fall of $\Delta T_h/P$, beginning from $p_s = 2.5\times 10^{12}$ cm^{-2}, which corresponded to the onset of filling of the second quantum subband deduced from the conductance measurements and from the Shubnikov-de Haas oscillations. A further increase in p_s caused $\Delta T_h/P$ to pass through a minimum and then it began to rise in the same way as τ_ε in the case of the (100) surface of undeformed samples.

It therefore follows from these results that the main feature of the energy relaxation time was its strong dependence on the surface orientation and on the presence or absence of deformation.

In addition to the dependences $\tau_\varepsilon(p_s)$, we also determined the dependences of the energy relaxation time of $2D$ holes on the lattice temperature. Figure 2 shows the dependences $\tau_\varepsilon(T_L)$ obtained for samples with the (111) and (100) surface orientations and a density $p_s = 3.6\times 10^{12}$ cm^{-2}. It is clear from this figure that the experimental dependence obeyed $\tau_\varepsilon \propto T^{-p}$, where $p = 3.1 \pm 0.5$, and it was independent of the surface orientation. A similar result was obtained for $p_s = 2.5\times 10^{12}$ cm^{-2} and the power exponent in this case was $p = 3.5 \pm 0.5$.

4. DISCUSSION OF RESULTS

1. Temperature dependence of the relaxation time τ_ε

Two-dimensional carriers in inversion channels may be scattered by surface and bulk (volume) acoustic phonons.[3,8,9,17-19] It was shown in Refs. 8 and 18 that in both cases we have $\tau_\varepsilon \propto T_L^{-3}$ and the temperature dependence is insufficient to distinguish one energy relaxation mechanism from the other. However, an analysis of the scattering by surface phonons shows that this mechanism can be ignored compared with the scattering by bulk phonons if the temperature is sufficiently low.[18,19] The energy relaxation time for the scattering by bulk phonons is described by[18]

$$\tau_\varepsilon = \frac{\pi^2 k (T_h^2 - T_L^2)}{6\varepsilon_F}\left\langle\frac{d\varepsilon}{dt}\right\rangle^{-1},$$

$$\left\langle\frac{d\varepsilon}{dt}\right\rangle = \frac{3\zeta(5)(2m)^{1/2}\Xi^2 k^5 T^4}{\pi\rho\hbar^4 s^4 \varepsilon_F^{1/2}}\Delta T_h, \tag{3}$$

where Ξ is the deformation potential constant; s is the velocity of sound; m is the electron mass; ρ is the density of Si. Equation (3) is derived on the assumption that $q_{\text{ph}} \ll 2k_F$, where k_F is the Fermi wave vector of an electron and q_{ph} is the momentum of a phonon corresponding to the maximum of the electron-phonon interaction (in our case, this momentum is $q_{\text{ph}} = 3.9kT/\hbar s$); this equation applies also if $q_{\text{ph}} l > 1$, where l is the mean free path of an electron measured using its momentum in the case of scattering by impurities. These conditions are satisfied only in few experimental situations. It is reported in Refs. 3, 9, and 9 that $\tau_\varepsilon \propto T^{-p}$, where $p = 2$ for high-mobility samples ($\mu = 10^4$ cm$^2\cdot$V$^{-1}\cdot$sec^{-1})[3], $p = 3$ for samples with $\mu = 10^3$ cm$^2\cdot$V$^{-1}\cdot$sec^{-1}, and $p = 3$ for samples with low and high electron mobilities.[8] It has been shown recently[20,21] that in the $2D$ case the electron-phonon interaction is enhanced when the phonon wave vector becomes comparable with $2k_F$. This may give rise to the dependence $\tau_\varepsilon \propto T_L^{-2}$ at temperatures such that $q_{\text{ph}} > 2k_F$ and to the dependence $\tau_\varepsilon \propto T_L^{-4}$ when $q_{\text{ph}} \lesssim 2k_F$. In all the investigated experimental situations we have $q_{\text{ph}} \lesssim 2k_F$ in the temperature range $1.5\ \text{K} < T < 10\ \text{K}$, so that the correct dependence $\tau_\varepsilon(T_L)$ can be found by a more careful analysis, as was done in Refs. 3, 8, and 9. When the density of $2D$ holes corresponds to the dependence $\tau_\varepsilon(T_L)$ shown in Fig. 6, the momentum q_{ph} becomes comparable with $2k_F$ at 12 K, i.e., in our case the condition $q_{\text{ph}} \ll 2k_F$ is satisfied quite well. Therefore, the experimentally determined dependence $\tau_\varepsilon \propto T^{-p}$, where $p = 3.3 \pm 0.7$, is not in conflict with the theoretical predictions made in Ref. 18 see Eq. (3)].

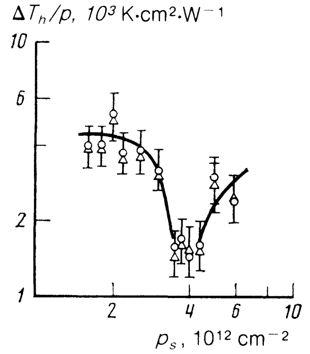

FIG. 5. Dependences of $\Delta T_h/P$ on p_s for samples with the (110) orientation (group No. 6): the points correspond to $\Delta T_h = 0.25$ K and the triangles to $\Delta T_h = 0.35$ K; $T_L = 1.75$ K.

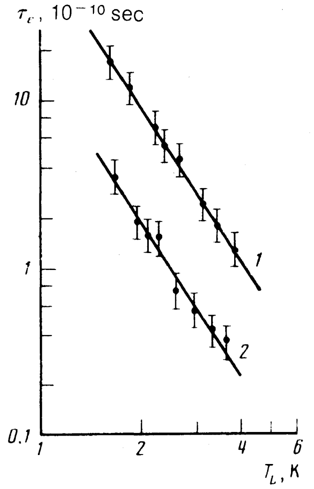

FIG. 6. Dependences of τ_ε on the lattice temperature T_L for samples with different orientations of the surface ($p_s = 3.6\times 10^{12}$ cm^{-2}): 1) sample of group No. 4, (111) orientation; 2) sample of group No. 1, (100) orientation.

2. Dependence of the relaxation time on the density of carriers in a channel

The relationship (3) predicts also an increase in the relaxation time τ_ε on increase in p_s in accordance with the law $\tau_\varepsilon \propto p_s^{1/2}$. However, we can see from Fig. 4 that in the case of the (111) orientation and also for MIS-SOS structures the relaxation time τ_ε decreases on increase in the hole density. Such a dependence is reported in Ref. 8 for an electron $2D$ gas in low-mobility samples. The reduction in τ_ε on increase in p_s may be due to impurity scattering. It is known that the electron-phonon interaction depends on the ratio of the phonon wave vector to the mean free path of an electron.[22] If $q_{\rm ph} l < 1$, an analysis of the electron-phonon interaction[22] shows that the time τ_ε becomes proportional to T_L^{-4} and decreases on increase in the mean free path. In our case we have $q_{\rm ph} l \approx 1$–2.5 and the contribution of phonons with the wave vectors satisfying $q_{\rm ph} l < 1$ to the energy relaxation process may be sufficient to influence the dependence $\tau_\varepsilon (p_s)$. The reduction in τ_ε on increase in p_s may be due to an increase in the mean free path which does indeed increase in the investigated structures on increase in p_s, but a more detailed analysis of this hypothesis will require a theory allowing for the impurity scattering. Another explanation relates the reduction in τ_ε to an increase in the deformation potential constant.[8] However, in this case we can describe the dependence $\tau_\varepsilon (p_s)$ for holes at the (111) surface only if we assume that an increase of p_s from 1.5×10^{12} to 5×10^{12} cm^{-2} increases the deformation potential constant Ξ from 15 to 35 eV, i.e., it is necessary to assume that the inversion channels are characterized by an anomalously large deformation potential constant.

We shall consider the $\tau_\varepsilon (p_s)$ dependence for holes near the (100) surface of undeformed silicon (Fig. 4b). In this case we observed two features of the behavior of τ_ε, different from that of the holes at the (111) and (100) surfaces in the case of MIS-SOS structures: firstly, the value of τ_ε was less than in the case of the (111) and (100) orientations in MIS-SOS structures and, secondly, τ_ε did not decrease but increase on increase in p_s. This behavior may be due to filling of two quantum subbands, because when the Fermi level reaches the bottom of a subband, the density of states of $2D$ carriers increases and new channels of the scattering by phonons appear (these are associated with intersubband transfer). The first and second factors should reduce strongly τ_ε as the Fermi level passes to the second quantum subband. However, we do not know the reason for the rise of τ_ε on increase in the hole density. This may be due to a reduction in the rate of intersubband transfer induced by phonons.

5. CONCLUSIONS

An investigation of the anomalous magnetoresistance of a hole $2D$ gas at the surface of silicon subjected to heating electric fields provides a simple and effective method for the determination of the temperature of holes when they are heated by an electric field. We used this method to investigate the relaxation time of holes scattered by phonons as a function of the lattice temperature, of the hole density, and of the orientation of the silicon surface, and also in the presence of isotropic deformation. It was established that whereas the dependence of the relaxation time on the lattice temperature was the same for all the investigated samples, $\tau_\varepsilon \propto T_L^{-(3.3\pm 0.7)}$, the value of τ_ε and its carrier-density dependence were greatly affected by the surface orientation. It was concluded that the orientational dependence of τ_ε was associated with the nature of filling of the second quantum subband in samples with the (100) and (111) surface orientations. It was shown that the currently available theory of the electron-phonon interaction in two-dimensional systems fails to provide a complete description of the experimental results obtained in the present study and it is necessary to generalize this theory so as to allow for the impurity scattering and also for intersubband transfer.

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