Weak localization in InSb thin films heavily doped with lead

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We study the weak localization (WL) in three-dimensional polycrystalline thin films of InSb. The films are closely compensated showing the electron concentration $n>10^{16}$ cm^{-3} at the total concentration of the donor- and acceptor-type structural defects $N_t>10^{18}$ cm^{-3}. Unless Pb doped, the InSb films do not show any measurable or show very small WL effect at 4.2 K. The Pb doping to the concentration of the order of 10^{18} cm^{-3} leads to pronounced WL effects below 7 K. From the comparison of the experimental data on temperature dependence of the magnetoresistivity and sample resistance with the WL theory, the dependence of the phase destroying time $\tau_\varphi(T)$ is determined. It is concluded that the dephasing is connected to three separate processes. The first is due to the spin-orbit scatterings and is characterized by temperature-independent relaxation time $\tau_{so}\simeq 10^{-12}$ s. The second is associated with the electron-phonon interaction ($\tau_i\sim T^{-3}$). The third dephasing process is characterized by temperature-independent relaxation time $\tau_c=(1-7)\times 10^{-12}$ s, which is tentatively ascribed to inelastic scattering at extended structural defects. The resulting time τ_φ shows saturation in its temperature dependence for $T\to 0$. The temperature dependence of the resistance can be explained by the electron-electron interaction for $T<1$ K, and by the WL effect for $T>2$ K.

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I. INTRODUCTION

Because of its unique physical properties, InSb is one of the most interesting materials for the investigation of the weak-localization (WL) effects. The critical electron concentration n_{cr} for the metal-insulator transition in InSb is very small, about 10^{14} cm^{-3}. The small effective mass of electrons, $m^*=0.014\,m_e$, and a large dielectric constant, $\varepsilon_s=17.5$, cause the effective Bohr radius to be very large, $a_B^*\simeq 73$ nm. As a consequence, the nonideality parameter determining the importance of e-e interactions, $k_F a_B^*$ is large for $n>n_{cr}$, and WL theory is applicable at relatively low electron densities n. In spite of those advantages as offers the metallic InSb, only several teams studied WL in this semiconductor.[1–4] In all papers, bulk crystals of InSb with $n<5\times 10^{15}$ cm^{-3} were studied.

In the present paper we investigate the WL effects in three-dimensional (3D) polycrystalline films of InSb heavily doped with electrically neutral Pb. The background effective donor concentration in the films is $(0.2–2.0)\times 10^{17}$ cm^{-3}, which means that we study the samples with much higher electron concentration. Hence, we expect that the quantum corrections should be related mostly to localization. Note that the results of Ref. 2 demonstrated that the corrections are due to the interaction.

In our samples of InSb⟨Pb⟩ films, the WL effect is observed at $T\leqslant 7$ K and is also much more pronounced in the magnetoresistance (MR) as compared to the earlier observations. A particular feature of the samples is a clearly marked effect of the SO interaction (positive MR) at the lowest magnetic fields. The spin-orbit (SO) interaction was not observed in the previous investigations on InSb doped with shallow donors. The presently observed SO interaction seems to be associated with the Pb doping, and is due to the large atomic number of lead.

For the interpretation of our experimental results we use the formulas for WL corrections[5–8] accounting for strong SO interaction and Zeeman splitting of spin-up and -down electrons (Landé factor $g=-51.3$). It should be noted that in Ref. 9, dedicated especially to the analysis of localization and interaction effects in InSb, only Zeeman splitting has been taken into account.

The investigation of the WL have acquired a new impact in recent years due to the problem of the temperature dependence of the electron dephasing time.[10] Our paper is also relevant to this problem.

The paper is arranged as follows. In Sec. II we describe the preparation method of InSb films and their doping with Pb. This section is also devoted to the interpretation of the inherent electrical properties of the InSb films. In Sec. III we discuss the WL effects observed below 7 K. Section IV summarizes our conclusions.

II. SAMPLE PREPARATION AND CHARACTERIZATION

The thin films of InSb were obtained by the flash evaporation method. Details of these procedures are given elsewhere.[11] The films are of polycrystalline nature with grains randomly crystallographically oriented in relation to the substrate.[12] The grain diameter, at a given deposition temperature, depends on the crystallographic orientation and

TABLE I. Electrical properties of the InSb⟨Pb⟩ films at 4.2 K as obtained from the Hall measurements. In the parentheses are given the data obtained from the curve fitting.

No	d, μm	μ, $cm^2/V\,s$	$n\times10^{-16}$ cm^{-3}
732	2.1	1080 (3500)	1.6 (1.6)
727	2.1	760 (830)	50 (15)
725	1.6	2770 (3000)	13 (1.9)

increases with the deposition temperature. The average grain diameter is about 0.1 μm.

It is known[13] that polycrystalline InSb films have electrical properties governed by structural defects. Without any intentional doping they are of *n* type. The lead doping, up to the solubility limit 3×10^{18} cm^{-3}, has no electrical influence on the doped InSb films, except for the lowest temperatures. This electrical neutrality of lead has been explained by a particular incorporation into InSb lattice.[14] Lead incorporates to the InSb matrix in pairs substituting the neighbor pairs In-Sb. In this sense Pb is an isoelectronic impurity in InSb. However, in our samples the solubility limit is overrun and in result the InSb⟨Pb⟩ films have microscopic inclusions of lead. Detailed investigations show[14,15] that a part of the inclusions can transit to superconductivity below 5 K.

We studied four samples: 732, 725*A*, and 725*B*, obtained at the substrate temperature $T_s=370\,^\circ$C, and 727 obtained at $T_s=340\,^\circ$C. Their parameters are given in Table I. Because samples 725*A* and 725*B* were obtained at the same conditions, and their parameters are similar, we present only parameters of sample 725*B*. In the table, d is the film thickness and μ is the electron mobility.

The dependence of resistance of all InSb⟨Pb⟩ films on temperature and magnetic field is of the same character, but different in details. In Fig. 1(a) we present results for sample 727 below-room temperature. This dependence is typical for polycrystalline films, except for the low temperature region below 7 K. The sharp resistitance increase with the decreasing T, shown in the inset, has been observed only in Pb-doped InSb films. We ascribe this low-temperature increase in resistance to the WL effect. The transition to the localization does not always have such an abrupt form: for sample 725*A* it is smoother.

Figure 1(b) shows an example of the MR measurements in InSb films at 4.2 K. Since InSb has an isotropic conduction band, any classic longitudinal MR should not be observed. Also the magnitude of the positive transversal MR is higher than the expected for uniformly doped InSb having the same electron concentration. The observed longitudinal MR as well as the relatively large transversal MR have to be associated with a nonuniform distribution of the charged defects. In order to explain the observed effects, we assume that the polycrystalline InSb thin films show not only a large number of defects of the donor- and acceptor-type but also that their compensation degree fluctuates strongly. Such fluctuations can, for example, be generated at grain boundaries.

With this assumption we adopt the explanation of the galvanomagnetic properties of compensated bulk *n* InSb proposed by Aronzon *et al.*[4] In *n* InSb, due to the low density of states and high dielectric constant, the compensation fluctuations can create macroscopic potential fluctuations. In result, the electrons are located in potential wells separated by potential barriers. Thus, the electric conduction takes place in a material composed of macroscopic areas of a metal-like phase separated by regions of an insulating phase, and by that is of percolating character. In this model, the measured macroscopic electron mobility is thermally activated, and hence the resistivity decreases with increasing temperature. The macroscopic mobility, as measured in the Hall experiments, is thus limited mainly by the percolation. In such a case the current lines are of zigzag shape, and the measured MR has both the transversal and longitudinal component. Therefore, the assumed percolative conduction model explains both the temperature dependence and the magnetic field dependence of the sample resistivity shown in Figs. 1(a) and 1(b).

We now examine the low-temperature region where the WL effects occur. Since pronounced localization effects take place only in samples doped with Pb, we consider a possible effect of Pb doping on both elastic τ and phase τ_φ relaxation times (here τ is defined as the microscopic magnitude). When τ changes due to the doping with Pb, the macroscopic mobility does not change substantially since it is mainly limited by the percolation. Therefore, in frame of this model, we do not rule out a decrease in the microscopic mobility due to the Pb doping. However, this decrease cannot cause any dra-

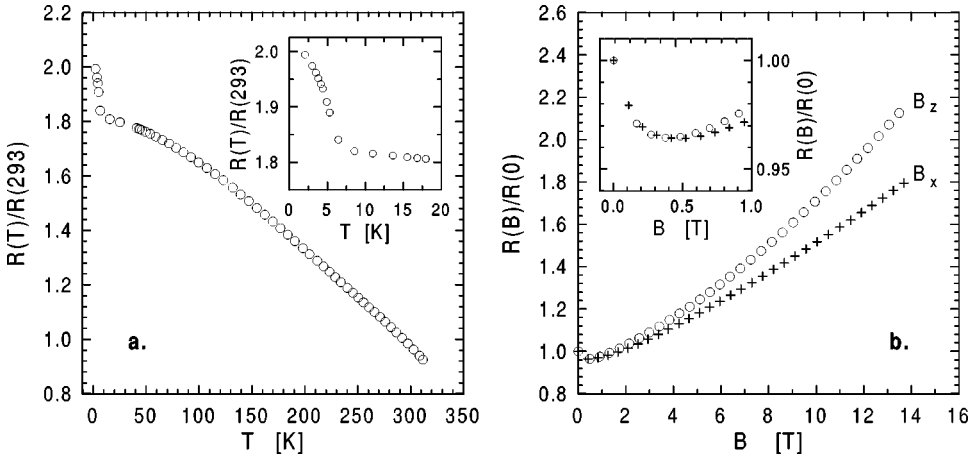

FIG. 1. (a) The temperature dependence of resistivity of InSb⟨Pb⟩ film (sample 727). (b) the magnetic-field dependence of the magnetoresistivity for the same sample at 4.2 K. B_z and B_x are the directions of magnetic field towards the sample. At B_z the transversal MR is measured, and at B_x the longitudinal MR is measured.

matic changes in the WL observation, because the WL correction in 3D case depends on the relaxation time as $\sqrt{\tau}$.[5,6] We believe that to understand the role of Pb doping, it is important to take into account that the neutral Pb atoms interact with electrons by short-range potentials, like strongly screened ionized impurities in metals. Large number of such defects creates necessary conditions for diffusive motion of electrons, which results in the WL effect. The suggestion that the WL is related to the electron scatterings on Pb atoms can further be confirmed by the antilocalization effect due to the SO interaction. According to the theory,[16] the SO scattering depends on the impurity atom mass as Z^4. Recent theoretical results for Mn suggest that the dependence be as Z^2 and the scattering can also depend on the impurity valency.[17] Thus, the theory predict strong SO scattering from heavy impurities. It should be mentioned that in previous studies performed on InSb crystals,[1–4] no SO effects have been observed.

III. WEAK-LOCALIZATION EFFECTS

The parameters of the samples determined from the Hall measurements at $T \simeq 7$ K are presented in Table I. Using these parameters one can estimate that the condition of effective three dimensionality,[5,6] $l_\varphi \ll d$, is fulfilled in all samples. In sample 732 the condition $1/k_F l \ll 1$ is not fulfilled, which means that for that sample the WL theory might not be applicable. Also, for this sample the magnetic freezing critical field turns out to be lower than for the other samples. However, even in this case the magnetic freeze-out is not likely to occur. The magnetic freeze-out field was estimated from the relationship $n(a_B l_B^2)^{1/3} \simeq 0.34$,[2] where $l_B = (\hbar/eB)^{1/2}$. In our case, it is higher than 2 T, and the magnetic freeze-out is negligible. In the field region $B < 0.3$ T, the classical magnetoconductivity of the samples is negligible ($\mu B \ll 1$).

In all samples the dependence of resistivity on magnetic field for $B < 0.3$ T and $T < 7$ K, is such that it first increases and then decreases with magnetic field. A typical example is shown in Fig. 2. The positive MR region at the lowest magnetic fields can be explained within the WL theory as the result of SO interaction.[8,5] In order to perform theoretical curve fitting to the experimental points, we adopt Kawabata's approach to MR,[18] generalized to account for the SO coupling and Zeeman splitting. The contribution from singlet Cooperon containing Zeeman splitting is

$$\Delta\sigma_s(B) - \Delta\sigma_s(0) = \frac{e^2}{4\pi^2\hbar l_B} \sum_{n=0}^{\infty} [P_{1/2}^{-1}\cos(\varphi_1/2) - 2P_1\cos(\varphi_2/2) + 2P_0\cos(\varphi_0/2)] \quad (1)$$

and that from triplet Cooperon containing SO scattering

$$\Delta\sigma_t(B) - \Delta\sigma_t(0) = -\frac{3e^2}{4\pi^2\hbar l_B} \sum_{n=0}^{\infty} \left[\left(n + \frac{1}{2} + \delta_{so} \right)^{-1/2} - 2\left(\sqrt{n+1+\delta_{so}} - \sqrt{n+\delta_{so}} \right) \right], \quad (2)$$

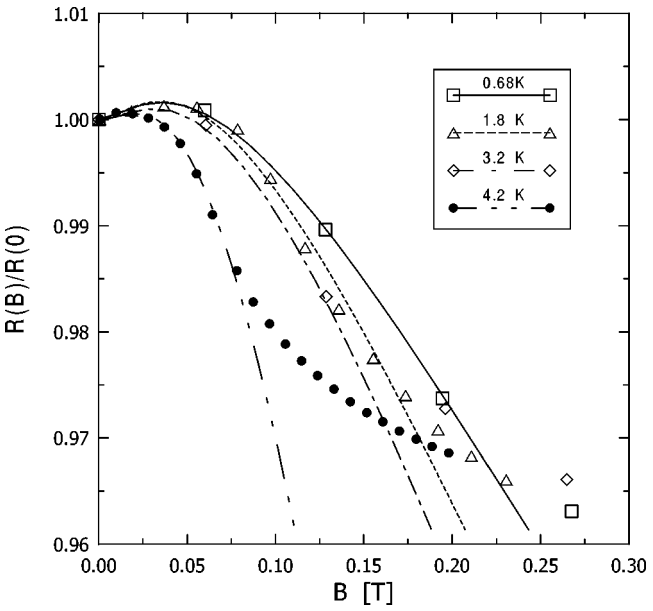

FIG. 2. Low-field magnetoresistivity of sample 727 at various temperatures. The curves are fittings of the WL theory to the experimental points.

where $P_s = [(n+s+\delta)^2 + \nu^2]^{1/4}$, $\delta = l_B^2/4D\tau_\varphi$, $\delta_{so} = (l_B^2/4D)(1/\tau_\varphi + 4/3\tau_{so})$, $\nu = g\mu_B/4eD$, $\varphi_s = \arctan[\nu/(n+s+\delta)]$, τ_φ is the phase relaxation time, D is the diffusion constant, and μ_B is the Bohr magneton. The total localization correction is the sum of Eqs. (1) and (2). We used Eqs. (1) and (2) for fitting the theoretical curves to the experimental dependences of MR at low magnetic fields and various temperatures. To fit the MR curves, we had to choose four parameters τ_φ, τ_{so}, n, and μ and their temperature dependencies. We assumed that τ_{so} and n are temperature independent, and μ can be only weakly dependent on T. The assumptions for n and μ are conclusions from the measurements, whereas that for τ_{so} is the common one.[19] An example of the fitting for sample 727 is shown in Fig. 2.

Sample parameters, obtained from the curve fittings, are given in Table I in parentheses. It was impossible to reach the values of n and μ obtained from the Hall measurements. In the case of sample 732 we found an increase in μ by a factor of about 3. This means that the microscopic mobility in this sample, as expected, is higher than the macroscopic one. With this higher mobility the condition $1/k_F l < 1$ is fulfilled for this sample.

In the case of samples 725 and 727, we found a relatively small increase in the mobility along with a considerable decrease in the electron concentration. The origin of this discrepancy appear to be the Pb inclusions. As was shown in Ref. 14, the inclusions have short-circuiting effects on the Hall voltage, and in the result the determined electron concentration is higher than the actual one.

In our curve fitting of the MR measured at different temperatures, we assumed that the theoretical description has to use the same set of parameters τ_{so}, n, and μ. This assumption appeared to be very restrictive and resulted in a considerable uncertainty in the determination of τ_φ (see Fig. 3). Moreover, to obtain improved fits we were forced to intro-

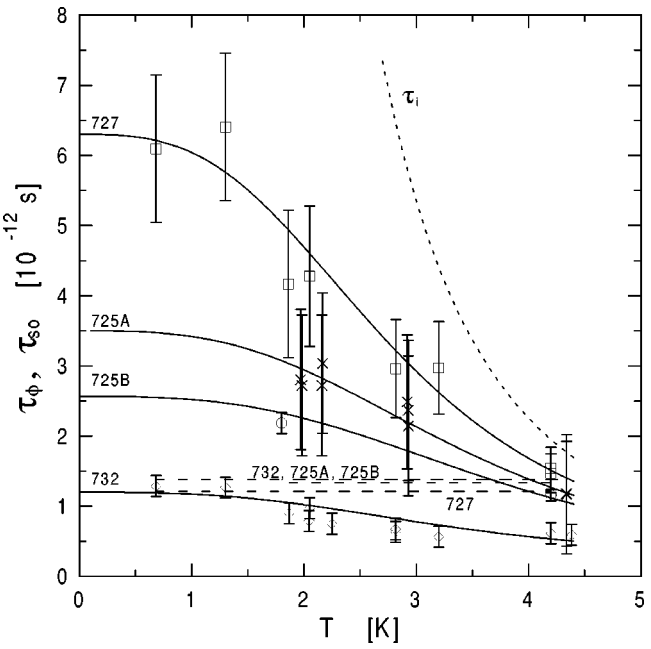

FIG. 3. Temperature dependencies of the relaxation times for samples 725*A*, 725*B*, 727, and 732 as obtained from the theoretical curve fittings to the experimental MR data. The solid curves are the values of τ_φ, the dashed lines are the values of τ_{so}, and the dotted line $\tau_i(T)$ given by Eq. (3).

duce into $\Delta\sigma$ a T-dependent prefactor $\alpha(T)$. The value of α at $T=4.2$ K is 1.0 for sample 732, 0.90 for sample 727, and 0.94 for sample 725*B*. The value of $\alpha(T)$ at $T=0.68$ K is 0.87 for sample 732 and 0.76 for sample 727. Sample 725*B* has not been measured at 0.68 K, but at $T=1.8$ K it has $\alpha=0.81$. Therefore, the prefactor introduces small corrections to the calculated curves mainly at the lowest temperatures.

It should be mentioned that in previous studies[1,2,4] a constant prefactor was also introduced because the magnitude of MR was always smaller than that predicted by the theory. The value of the prefactor was in the range $\alpha=0.02-0.55$. In the present case there is no problem with the magnitude of the effect, but with its temperature dependence. The dependence $\alpha(T)$ correlates with the dose of Pb obtained by a given sample. The doses obtained by samples 725 and 727 were higher than that obtained by sample 732. We think that the temperature dependence of α can be related to this part of Pb inclusions that can transit to superconductivity, and owing to the proximity effect can slightly decrease the resistance at the lowest temperatures.

The high concentration of Pb may also suggest that the Maki-Thompson corrections[20] can play a significant role in the temperature dependence of the conductivity. The Maki-Thompson corrections change $\Delta\sigma$ by a factor $\beta(T)=1-\alpha(T)$, and $0\leqslant\beta(T)\leqslant 1$. However, we found that the temperature dependence of α in our samples, especially in sample 727, cannot be satisfactorily explained by Maki-Thompson corrections.

The temperature dependences of τ_φ and τ_{so} obtained from the fitting are presented in Fig. 3. As is seen, the obtained SO relaxation time is nearly the same in all samples and is $\tau_{so}\simeq 1.2\times 10^{-12}$ s. This can be compared with the data for 2D metallic films covered with a monolayer of impurities.[21] For the heaviest impurity atoms a value of $\tau_{so}\leqslant 10^{-12}$ s is characteristic, which is close to our value. It is known that the probability of SO scattering is proportional to the atomic number of the impurity and the inverse of the elastic relaxation time. A detailed value is determined by the relevant conduction-band parameters.[21,22] In particular, the relaxation times τ_{so} should be proportional to the electron mobility. Actually, such correlation in our samples is not observed. This can be explained by a difference in the Pb concentrations between different samples. Such a dependence of τ_{so} on the heavy impurity concentration was observed in Mg films doped with Bi.[19]

As is seen in Fig. 3, at 4.2 K τ_φ for all samples is of the order of 10^{-12} s, and thus is close to the value of τ_{so}. The most striking feature of τ_φ is its weak temperature dependence. Usually, a dependence $\tau_\varphi^{-1}\sim T^p$ is assumed for the inelastic processes. In particular, $p=2$ and $p=3$ for the *e-e* interaction and the electron-phonon interaction in the clean limit,[5,6] respectively. Dynes *et al.*[1] found $\tau_\varphi\sim T^{-3}$ in the temperature range 0.05 to 1.5 K. Their data give $\tau_\varphi=1.3\times 10^{-12}$ s at 4.2 K, a value close to our result. On the other hand, Mani *et al.*[3] obtained between 0.5 and 4.2 K, $\tau_\varphi\sim T^{-2}$ with $\tau_\varphi=4\times 10^{-12}$ s at 4.2 K.

Saturation of τ_φ at $T\to 0$ has been usually attributed to the effect of magnetic impurities.[8] However, this mechanism cannot be responsible for the presently observed saturation of τ_φ because in our samples important could be magnetic impurities in concentration $>10^{17}$ cm^{-3}. Such a large uncontrolled doping should be ruled out from the viewpoint of our technology. Moreover, the solubility limit of magnetic impurities in InSb (Fe, Co, Ni) is below 10^{14} cm^{-3}.[23]

Saturation of τ_φ at $T\to 0$ in the absence of magnetic impurities has been recently reported[24,25] and critically discussed.[26] While the existence of the saturation is still a subject of controversy, it seems to emerge that an explanation of the observed weak temperature dependence of τ_φ in some disordered metals is an additional T-independent relaxation mechanism. An example of such a mechanism is an inelastic scattering from two-level centers.[10] In our case we assume that the mechanism can be associated with inelastic interactions of the conducting electrons in the course of their transmission through potential barriers located at extended structural defects such as grain boundaries. We can expect the presence of dangling bonds, acting as two-level centers, in the vicinity of the grain boundaries. We have also estimated the possible effect of high-frequency noise[26] but found that it is negligible in our case.

Thus, we make the substitution $\tau_\varphi^{-1}=\tau_i^{-1}+\tau_c^{-1}$, where τ_i is the dephasing time related to an intrinsic mechanism, characterizing InSb, and τ_c is a dephasing saturation time, which can be related to the grain size L_c by $\tau_c=L_c^2/D$. Assuming that $\tau_i\sim T^{-p}$, the best fit is obtained for $p=3$, corresponding to the electron-phonon interaction in pure metals.[27,28] The solid curves in the Fig. 3 are calculated with

$$\tau_i=1.95(4.2/T)^3 10^{-12}\ \text{s}. \tag{3}$$

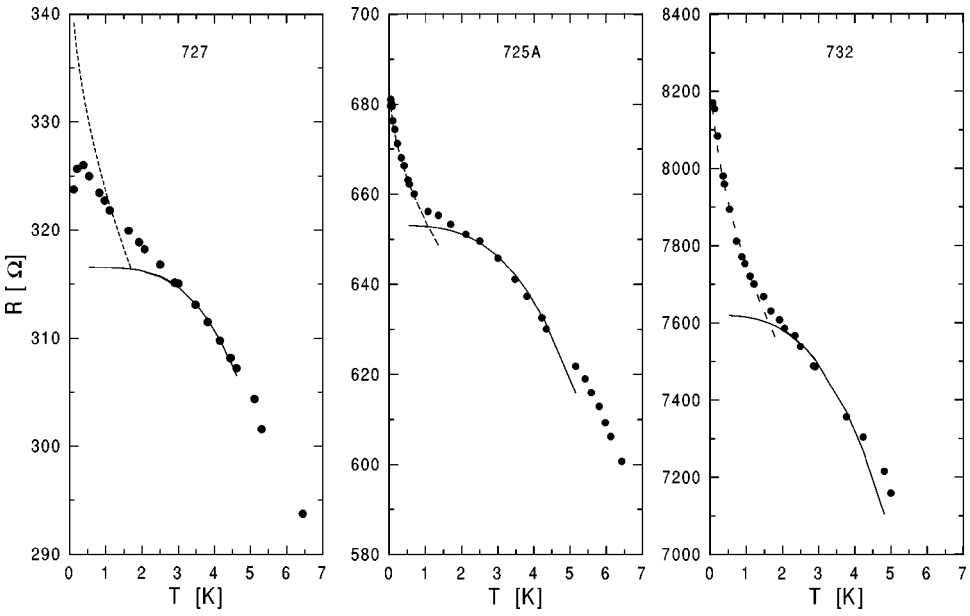

FIG. 4. The temperature dependence of resistance of samples 727, 725, and 732 between 40 mK and 7 K. The solid lines are calculated from Eqs. (4) and (5) as explained in the text.

The values of τ_c used in the calculations can be read out from Fig. 3 as τ_φ at $T=0$.

The temperature dependence of the sample resistance between 0.04 and 7 K are shown in Fig. 4. They can be interpreted using the WL theory taking into account both WL and interaction corrections. The localization correction to the conductivity,[5] which includes SO coupling, can be presented as

$$\delta\sigma_{loc}=\text{const}+\frac{e^2}{4\pi^2\hbar\sqrt{D\tau_\varphi}}\left[3\left(1+\frac{4\tau_\varphi}{3\tau_{so}}\right)^{1/2}-1\right] \quad (4)$$

and the interaction correction is

$$\delta\sigma_{int}=\text{const}_1+2.5\frac{\sqrt{2T}e^2}{6\pi^2\hbar\sqrt{D}}, \quad (5)$$

where we take into account only the exchange contribution,[7] and do not consider the Maki-Thompson corrections.

The resistance below 1 K exhibits the dependence $R\sim T^{-1/2}$, shown by dashed lines in Fig. 4. Therefore, the *e-e* interaction is responsible for $R(T)$ in this temperature region.[5,6] The exception is sample 727 that shows a maximum in T dependence. We ascribe this anomaly to superconducting Pb inclusions, decreasing the resistance.

At higher temperatures, the temperature dependence of the samples resistance can be described by Eq. (4). This dependence is shown in Fig. 4 by the solid lines. As is seen, between 2 and 5 K the character of the temperature dependence of resistance is well approximated by the calculated curves. Therefore, both MR at various T and $R(T)$ can be explained using the same dependence of $\tau_\varphi(T)$, in which τ_c plays an important role.

Sometimes one argues that the saturation of τ_φ is an artifact associated with the warming effect of the sample driving current.[25] In this connection we wish to point out the fact that in Fig. 4 the resistance sharply increases with decreasing temperature in the low-temperature region where the dephasing time saturates. This confirms that the hot-electron effects due to Joule heating do not take place. If Joule heating occurred, the temperature dependence of the resistance would saturate.

IV. CONCLUSIONS

We report the analysis of WL in 3D InSb films heavily doped with Pb. Doping with Pb results in pronounced WL effects: at temperatures below 7 K, the resistance rapidly increases, the magnitude and temperature range being considerably higher than those observed previously in pure InSb.[1–3] The relation of the WL effect to the presence of Pb impurities is confirmed by the positive MR observed at the lowest magnetic fields, which is apparently due to the SO scattering. To interpret the low-temperature MR, we used the Kawabata's formula[18] taking into account SO coupling and Zeeman splitting, and obtained the SO interaction time $\tau_{so}\simeq 10^{-12}$ s.

The fitting also supplied the temperature dependence of τ_φ, demonstrating its saturation for $T\to 0$. We show that this dependence can be explained if one assumed that τ_φ is a combination of an inelastic relaxation time $\tau_i(T)$ and a saturation time τ_c. The determined temperature dependence of inelastic relaxation τ_i can be associated with electron-phonon interaction. Its magnitude is in a good agreement with that obtained before.[1]

The relaxation time τ_c is assumed to be independent of temperature. In our samples it is in the range $\tau_c=(1\text{ to }7)\times 10^{-12}$ s. We suppose that it is associated with extended structural defects of InSb films, such as the grain boundaries. In this model the conductivity electrons are dephased by inelastic scatterings from electrons occupying the interface states, which have a nonvanishing density of states at the Fermi level. In such a model τ_c can be related to the grain size L_c by $\tau_c\sim L_c^2/D$. For the obtained values of τ_c one ob-

tains $L_c \simeq 100$ nm. This is a magnitude of correct order in our samples. Our dependence $\tau_\varphi(T)$ resembles that found by Lin and Kao[25] for a large group of disordered polycrystalline metals.

The dependence $\tau_\varphi(T)$ was used for the interpretation of the resistance $R(T)$ above 2 K. At lower temperatures, the dependence $R(T)$ can be explained by the *e-e* interaction. It should be noted that we were able to interpret both the temperature dependence of MR and $R(T)$ using the same temperature dependence of τ_φ and the other determined parameters.

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