Contribution of weak localization and electron-electron interaction, in corrective term "mT$^{1/2}$" of the metallic conductivity in n-type SiAs

Abdelghani Sybous [1], Abdelhamid El kaaouachi [1,*], Abdelfattah Narjis[1], Lhoussine Limouny[1], Said Dlimi[1], Bruno Capoen [2], Jamal Hemine[3], Rachid Abdia[1], and Gerard Biskupski [4]

1 Research Group in ESNPS, Physics Department, University Ibn Zohr, Faculty of Sciences, B.P 8106, Hay Dakhla, 80000 Agadir, Morocco.
2 C E R L A - FR CNRS 2416, Université des Sciences et Technologies de LilleI 59 655 Villeneuve d'Ascq Cedex France.
3 Laboratoire de Physique de la Matière Condensée, Faculté des Sciences et Techniques de Mohammadia, Département de Physique, Mohammadia, Morocco.
4 Laboratoire de Spectroscopie Hertzienne ,LSH équipe des semi-conducteurs, Bâtiment P5, Université des Sciences et Technologies de LilleI 59 655 Villeneuve d'Ascq Cedex France

Corresponding author: a.saybous@yahoo.fr

ABSTRACT: We present measurements of the electrical conductivity of barely metallic n-type SiAs that are driven to the metal-insulator transition (MIT) by impurity concentration. The experiments were carried out at low temperature in the range (3.48 - 0.00044 K) and with impurity concentrations up to $10.410^{16} cm^{-3}$. On the metallic side of the MIT, the electrical conductivity is found to behave like $\sigma = \sigma_0 + mT^{1/2}$ down to 0.44 *mK*. Physical explanation to the temperature dependence of the conductivity is given in metallic side of the MIT using a competition between two effects involved in the mechanisms of conduction, like electron-electron interaction effect, and weak localization effect.

Keywords:
SiAs semiconductor, low temperature, impurity concentration, metal-insulator transition, electron-electron interaction effect, weak localization effect.

I. Introduction

Biskupski et al. [1], and El kaaouachi et al. [2] have observed the metal-insulator transition (MIT) induced by an impurity concentration in barely metallic and compensated n-type InP. Using new analysis methods, they determined the critical magnetic field B_C for which the conductivity changes from a metallic behaviour to a variable range hopping regime.

In recent years it has become clear that not too close to the MIT, the equation for the temperature dependence of the metallic conductivity [3 - 5] is:

$$\sigma = \sigma\ (T = 0) + mT^{1/2} \qquad (1)$$

Where $\sigma(T = 0)$ is the zero temperature conductivity and *m* is the magnitude of the correction term. $\sigma(T = 0)$ and *m* were obtained by standard linear regression methods.

In the absence of the magnetic field, several authors have examined the behaviour of the magnitude *m* in different semiconductors [6-8]. They have shown that at *B=0 T*, the sign of the term *m* depends on the difference between the Hartree and the exchange terms.

In this paper, we examine the behaviour of the magnitude *m* with impurity concentration n. When the MIT is induced by an impurity concentration, several phenomena contribute to this corrective term "$mT^{1/2}$" among which are the electron-electron interaction effect, and the weak localization effect.

In the absence of the magnetic field the electrical conductivity can be written as:

$$\sigma = \sigma(T = 0) + \delta\sigma_{e-e\,interaction} + \delta\sigma_{Weak\ localization} \qquad (2)$$

where $\delta\sigma_{e-e\,interaction}$ and $\delta\sigma_{weak\,localization}$ are respectively the contributions of electron-electron interaction and weak localization effects of corrective term of the electrical conductivity σ.

In Fig. 1, we have plotted the electrical conductivity σ versus $T^{1/2}$ for different values of impurity concentration n between $8{,}67.10^{16}$ and $10{,}4.10^{16} cm^{-3}$ for a metallic SiAs sample with magnetic field equal 0 T. The experiments were carried out at low temperature in the range (0.9 -0.00033 K) and in impurity concentration up to $6{,}4.10^{17} cm^{-3}$. We have observed that m changes the sign in this interval of impurity concentration.

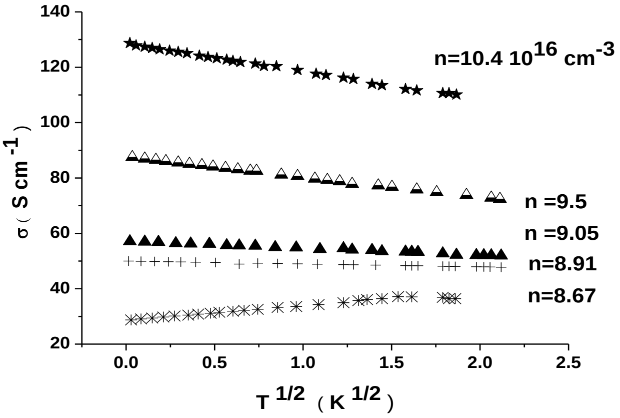

Fig. 1. Electrical conductivity σ versus $T^{1/2}$ for different impurity concentration

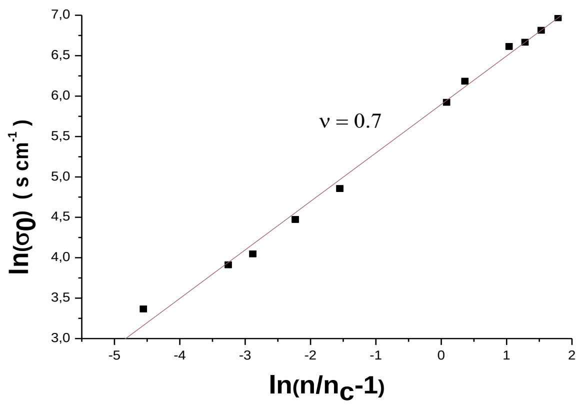

Fig. 2. Evolution of the $\ln(\sigma(0))$ against $\ln(n/n_c-1)$

II. Electron-electron interaction effect

The electron-electron interaction effect has been estimated by Altshuler et al. [9] and simplified by El kaaouachi et al. [2]. The simplified form of the contribution of electron-electron interaction effect to the electrical conductivity with a $T^{1/2}$ dependence is given by:

$$\delta\sigma(T,n)_{e-e.\mathrm{interaction}} = \left[\frac{e^2}{2\pi^2\hbar}\frac{F}{2}\left[1+\frac{F}{2}Ln\left(\frac{E_F}{k_BT}\right)\right]^{-1}\frac{2.3}{\sqrt{\frac{2eD}{\pi k_B}}}\right]\left[\frac{e}{\hbar}T\right]^{1/2} \quad (3)$$

Where D is a diffusion parameter of the middle given by :

$$\mathrm{D} = \mathrm{D}_0(n/n_c-1)^{\nu} \quad (4)$$

n_c is the critical impurety concentration. D_0 and ν are a constants $D_0=\frac{V_f^2\tau}{3}$, V_F and τ are respectively the speed at the Fermi level and the elastic scattering time. In other hand, following the work of Wegner [10], in the metal side of the TMI, the conductivity at zero temperature is given by:

$$\sigma(0)=\sigma_c\left(\frac{n}{n_c}-1\right)^{\nu} \quad (5)$$

In fig. 2 we plot the variation of the $\ln(\sigma(0))$ with the $\ln(n/n_c-1)$. This allows us to access to the slope ν $(\nu=0.7)$. And Fig.3, shows the evolution of the diffusion parameter D with the impurety concentration n.

III. Weak localisation effect

The weak localization correction has been calculated by kawabata [11] and developed by El kaaouachi et al.[2]. The expression obtained is given by:

$$\delta\sigma_{Weak\ localization} = -\frac{e^2}{2\pi^2\hbar}\sqrt{\frac{1}{DA}}T^{1/2} \quad (6)$$

where A is a constant given by:

$$A=\frac{2(E_F\tau)^2}{3^{3/2}k_B\hbar} \quad (7)$$

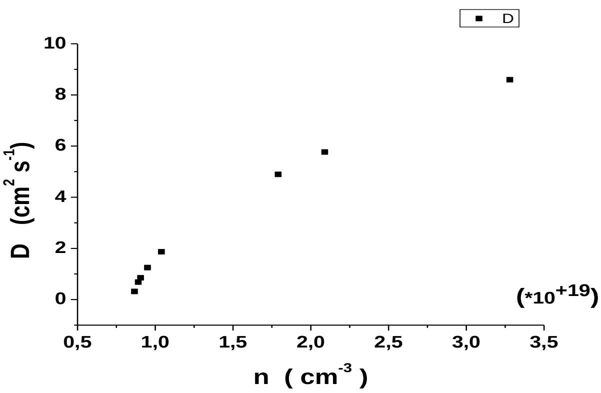

Fig. 3. Variation of the diffusion parameter D with impurety concentration n

IV. Results and discussion

We present in Table 1 some parameters of the SiAs sample. We have calculated the Hartree Fock constant F using two theoretical methods: the Thomas-Fermi approximation "F_{T-F}", and the Kleinman-Langreth dielectric function [12-13] "F_{K-L}"

$$F_{T-F} = \frac{\ln(1+x)}{x} \quad \text{where} \quad x = \left(\frac{2k_F}{K_{T-F}}\right)^2 \tag{8}$$

Where k_F is the Fermi vector and K_{T-F} is the Thomas-Fermi scattering vector.

$$F_{K-L} = \frac{\ln(1+\alpha)}{\alpha} \quad \text{where} \quad \alpha = \left(\frac{K_S}{2k_F}\right)^2 \tag{9}$$

where K_S is the scattering parameter given by:

$$K_S = K_F\left(\frac{2}{1+0.158\left(\frac{k_{TF}}{2k_F}\right)^2} - 1\right)^{1/2} \quad \text{and}$$

$$k_{TF} = \left(\frac{12\pi m^* n e^2}{4\pi\varepsilon\varepsilon_0\hbar^2 K_F^2}\right)^{1/2} \tag{10}$$

We have obtained for our sample $F_{T-F} = 0.099$ and $F_{K-L} = 0.893$.

Table 1. Some parameters of the SiAs sample.

Parameters	Symbol	value
Critical impurity concentration	n_c	$8.58 10^{18}\ cm^{-3}$
Fermi vector	k_F	*7.38 10^8m^-1*
Free path length	l	*186 Å*
Thomas-Fermi scattering vector	K_{T-F}	*2.26 10^8m^-1*
Parameter $k_F l$	$k_F l$	π
Elastic diffusion constant	D_0	*4.66 10^-4m^2s^-1*
Constant F_{T-F}	F_{T-F}	*0.099*
Constant F_{K-L}	F_{K-L}	0.*893*

Firstly, we have calculated separately the theoretical value of the magnitude *m* due respectively to electron-electron interaction effect, and weak localization effect using Equations (3) and (6). Then we compared these theoretical values with experimental values of *m*.

In Fig. 4, we plot experimental values of m and the corrective term to electrical conductivity σ due only to electron-electron interaction effect Eq. (3) in the both cases when F is calculated using Thomas-Fermi approximation "$F = F_{T-F}$" and using Kleinman-Langreth approximation "$F = F_{T-F}$".

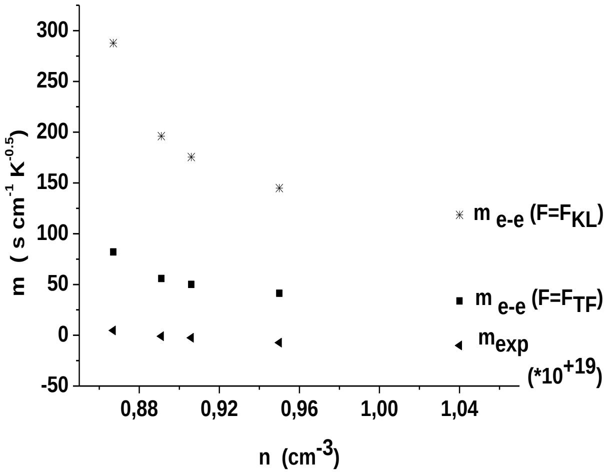

Fig. 4. Experimental and theoretical values with ($F=F_{TF}$ and $F=F_{KL}$) of magnitude m versus impurity concentration (contribution of electron-electron effect).

The electron-electron interaction effect contribution to *m* is positive and decreases slightly with impurity concentration. This decrease is larger when *F* was calculated using the Kleinman-Langreth approximation.

In Fig. 5, we plot experimental values of *m* and the corrective term to electrical conductivity σ due only to weak localization effect Eq.(6).

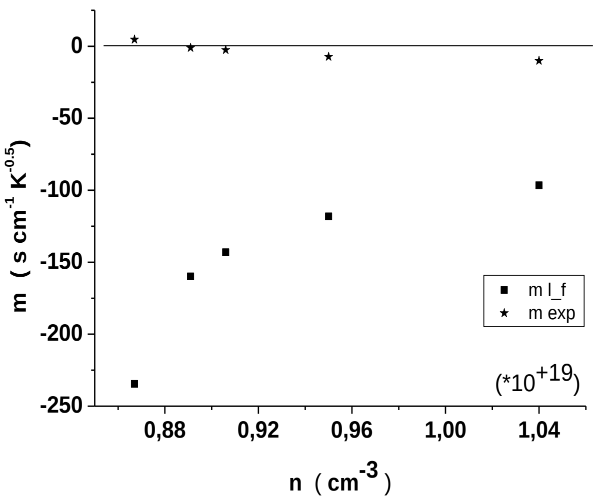

Fig. 5. Experimental and theoretical values of magnitude m versus impurity concentration (contribution of weak localization effect).

The contribution to m due to the weak localization effect vary with the impurety concentration and is negative.

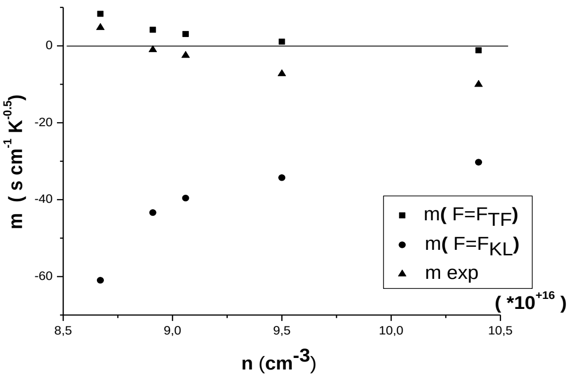

Fig . 6. Experimental and theoretical values of magnitude m versus impurity concentration using the sum of the two effects (e-e interaction effect and weak localization effect Eq. (2).

Secondly, we have calculated theoretical values of *m* using the sum of electron-electron interaction effect, and weak localization effect Equations (2), (3) and (6). The Hartree-Fock constant *F* was calculated using respectively the Thomas-Fermi approximation and the Kleinman-Langreth approximation.

The theoretical and experimental results of the magnitude *m* in corrective term "$mT^{1/2}$" of the electrical conductivity are shown in Fig. 6. We noticed that the experimental values of *m* are changing sign. We also noted that there is not a good qualitative agreement between experimental and theoretical results of magnitude m when $F = F_{K-L}$, but when the Hartree-Fock constant *F* was calculated in the Thomas-Fermi approximation ($F = F_{T-F}$) we observed a large discrepancy between experimental and theoretical results.

V. Conclusion

The experimental values of magnitude *m* are positive and vary slightly with the magnetic field. We can infer that the electron-electron interaction effect (positive contributions to *m*) is dominant over the weak localization effect (negative contribution to *m*). The summation of the three effects varies slightly with magnetic field. In previous work, El kaaouachi et al. [2] found that *m* changes sign from negative to positive when the magnetic field increases in InP sample. We have also obtained a better correspondence between theory and experiment for $F = F_{T-F}$.

References

[1] G. Biskupski et al., J. Phys Condens Matter. 3 (1991) 8417.
[2] A. El kaaouachi et al., Phys. Stat. Sol b. 241 No 1 (2004) 155-162.
[3] A. El kaaouachi et al., Physica B Condens Matter. 226 N°3 (1998) 226- 228.
[4] A. El kaaouachi et al., Physica B Condens Matter . 304 (2001) 377-381
[5] A. El kaaouachi et al., Semiconductors Sciences and Technology.18 (2003) 69-74.
[6] G. A. Thomas et al., Phys. Rev B 26 (1982) 2113
[7] G. A. Thomas et al., M. Paalmen, and T. F. Rosenbaum, Phys. Rev B 27 (1983) 3897
[8] W. N. Shafarman et al., Phys. Rev B 40 (1988) 1216.
[9] BL. Altshuler et al., Sov. Phys –JETP. 54(1981) 411.
[10] FJ. Wegner, Z. phys. B 35 (1979) 2007.
[11] A. Kawabata, solid state commun. 34 (1980) 431.
[12] L. Kleiman, Phys. Rev. 160 (1967) 585.
[13] DG. Langreth, Phys Rev. 181 (1967) 753.

