Transport properties of the electron gas in thin AlAs quantum wells: interface-roughness scattering

A Gold
Centre d’Elaboration de Materiaux et d’Etudes Structurales (CEMES-CNRS),
29 Rue Jeanne Marvig, 31055 Toulouse, France
E-mail: gold@cemes.fr

Abstract. For interface-roughness scattering and for zero temperature we compare theoretical results for the mobility of the two-dimensional electron gas present in thin AlAs quantum wells with experimental results for a well of width \( L = 45\text{Å} \). The importance of many-body effects (exchange and correlation) on the mobility is discussed. For the mobility reasonable agreement between theory and experiment is obtained by taking into account a density dependent effective mass and multiple-scattering effects, which lead to a metal-insulator transition.

1. Introduction
The study of a two-dimensional electron gas (2DEG) [1] in a quantum well (QW), made of AlAs, begun al long time ago [2]. For a recent review, see Ref.3. In this paper we compare experimental results on low temperature transport properties of thin AlAs QW’s [4] with theoretical results.

The experimental results on the low temperature mobility indicate that the following points are essential: (i) a metal-insulator transition (MIT) occurs at low electron density [4] and (ii) the effective electron mass increases with decreasing electron density [5]. Such a behavior has been seen before in Silicon MOSFET structures [6] and seems to be a general behavior of the 2DEG at low electron density, where the Wigner-Seitz parameter \( r_s \) is large. Therefore, we took these two essential issues into account to describe transport properties of the 2DEG [7]. In the present paper we discuss some additional results concerning many-body effects due to exchange and correlation.

2. Model and theory
We consider a quantum well of width \( L \) and the 2DEG is described by a longitudinal and density dependent effective electron mass \( m^* / m_e = 0.19 / (1 - N_{cm} / N) \), a perpendicular effective electron mass \( m_c = 1.1 m_e \) and the electron density \( N \) [7,8]. For the density \( N_{cm} \) of the divergent mass we use \( N_{cm} = 5 \times 10^{10} \text{cm}^{-2} \), in reasonable agreement with experimental results [5]. The valley degeneracy of this 2DEG in the AlAs QW is \( g_v = 1 \).

As the scattering mechanism we assume interface-roughness scattering, characterized by the average height \( \Delta \) of the roughness perpendicular to the QW, and by the length \( \Lambda \), the correlation length parameter of the roughness in the plane of the 2DEG [1]. The squared averaged random potential for QW’s is written as \( \langle |U(q)|^2 \rangle \propto m^* \Delta^2 \Lambda^2 \exp(-q^2 \Delta^2/4)/(m_e \Lambda^4 \langle L \rangle) \) [9]. Note, that a mass increase of...
$m'$ has a strong influence on interface-roughness scattering. Interaction effects are treated within the random-phase approximation (RPA) [1,10] and many-body effects are taken into account via the local-field correction (LFC) $G(q)$ [11]. We use an analytical expression for the LFC where exchange and correlation effects are taken into account [12]. If correlation effects are neglected the Hubbard approximation $G_H(q)$ is used for the LFC [11].

For the transport theory we apply the mode-coupling approach where multiple-scattering effects lead to a MIT at low electron density [10]. The mobility is written as $\mu(N > N_{MIT}) = \mu'(N) (1 - N_{MIT}/N)$ and $\mu(N < N_{MIT}) = 0$. The mobility $\mu'(N)$ represents the lowest order expression where multiple-scattering effects are neglected [1]. $A$ is the parameter which describes multiple-scattering effects and the MIT is defined by $A = 1$ [10]. The critical density $N_{MIT}$ of the MIT depends on $\Delta$ and $\Lambda$. Weak localization effects are not taken into account. It is well known that such effects are not relevant near the MIT [6]. For the density of the MIT we use the value $N_{MIT} = 7 \times 10^{10} \text{cm}^{-2}$, taken from experiment [4]. For more details concerning the model and the parameters used, see Ref.8.

3. Results for the mobility including many-body effects

Including the LFC into the screening function reduces the screening properties of the 2DEG. This is a know effect [11]. In the present case it means that the mobility is reduced when many-body effects via the LFC are taken into account [10]. We describe the mobility versus density data of an AlAs QW of width $L = 45 \AA$ [4] and we use the interface roughness parameters $\Delta$ and $\Lambda$ to fit the data. In the following we show that the reduction of the mobility due to the many-body effects can be compensated by a smaller value of $\Delta\Lambda$.

In figure 1 we show the mobility $\mu'$, calculated in lowest order, versus electron density, within different approximations for the local-field correction. In the RPA the exchange and correlation effects are neglected and the LFC is set to zero, see the dotted line. The RPA gives rise to a high mobility. For $G_H(q)$ only exchange effects are taken into account within the Hubbard approximation and correlation effects are neglected, see the dashed line. Exchange and correlation effects are taken into account for the solid line. This LFC was calculated in approximate, but analytical form [12]. Note the dramatic differences of the mobility found for the three approximations, especially at low electron density. It is known [11] that many-body effects beyond the RPA are negligible in the high density limit $r_s < 1$. However, the electron density $N'$, where $r_s = 1$, corresponds in AlAs QW’s to $N' = 4 \times 10^{12} \text{cm}^{-2}$ and experiments [4] are made in the range $r_s >> 1$. From mobility measurements on Silicon QW’s it was deduced that many-body effects are important at low electron density [13].

Figure 1. Mobility in lowest order versus electron density for the 2DEG in an AlAs QW of width $L = 45 \AA$. The solid line represents our calculation with exchange and correlation effects taken into account in the LFC. The dashed line represent the calculation with exchange effects. For the dotted line many-body effects are neglected, we used the RPA.
In figure 2 we use the Hubbard approximation for the LFC and show the calculated mobility versus density in comparison with the experiment [4]. Reasonable agreement is obtained by taking into account the MIT: the good agreement at low electron density $N < 3 \times 10^{11} \text{cm}^{-2}$ is conditioned by the presence of a MIT. At high density the lowest order result is in good agreement with the experiment. In order to fit the experimental results we used $\Delta \Lambda = 83.6 \AA^2$. For small density $k_F \Lambda \ll 1$, with $k_F$ as the Fermi wave number, one finds $\mu \propto 1/(\Delta \Lambda)^2$. This shows that one can use $\Delta \Lambda$ to compensate for a loss of mobility by using a finite LFC. The value $k_F \Lambda = 1$ in figure 2 corresponds to $N = 1.1 \times 10^{12} \text{cm}^{-2}$.

![Figure 2](image-url)  
**Figure 2.** Mobility versus electron density for the 2DEG in an AlAs QW of width $L = 45 \text{Å}$. The solid line represents our calculation where exchange effects are taken into account in the LFC (Hubbard approximation). The dotted line represents the lowest order result of our theory, without a MIT. The solid dots represent experimental results [4].

In figure 3 we show the mobility versus electron density when the LFC with exchange and correlation effects is included. Good agreement is obtained with experimental results [4] by taking into account a MIT, see the solid line [6]. A smaller value $\Delta \Lambda = 51 \AA^2$ than in figure 2 is used in figure 3 for the parameters of the interface-roughness scattering. The decrease of $\mu$ at low electron density is due to poor screening properties when correlation effects lead to a LFC $G(q = 2k_F) = 1$. Note that for
the strong correlation regime $r_s \to \infty$ is approached. Comparing the solid lines in figure 3 and figure 2 we conclude that correlation effects can be compensated to a certain amount by a different choice of the interface-roughness parameters. This is a important result of the present paper. In figure 3 the agreement between theory and experiment at low electron density $N \approx 3 \times 10^{10} \text{cm}^{-2}$ is again conditioned by the presence of a MIT. Comparing figure 2 with figure 3 we conclude that the presence of a MIT in the theory is essential for the agreement between theory and experiment. In Ref.6 we also calculated the critical density of the MIT: for a density dependent effective mass we found $N_{\text{MIT}} = 5.67 \times 10^{10} \text{cm}^{-2}$. However, $N_{\text{MIT}}$ depends on the value used for $N_{\text{cm}}$ and this value is not yet determined with high accuracy, see the scatter of the data in Ref.5.

The MIT found in the AlAs QW [4], if confirmed with other samples, is of great importance. We stress that the MIT in the 2DEG discussed so far occurs for a 2DEG with $g_s = 2$ on the surface of Silicon [6] and the MIT is determined by charged-impurity scattering. The MIT found in GaAs heterostructures [6] with $g_s = 1$ is also induced by disorder due to charged impurities, as discussed in Ref.14. In the case of AlAs QW’s our calculation suggests that the MIT is due to interface-roughness scattering. We stress that the MIT due to interface-roughness scattering in thin QW’s has been predicted a long time ago [9].

Most transport calculations for the 2DEG are made in lowest order and using the RPA. In some calculations the Hubbard approximation is used for the LFC. Figure 1 shows which kind of differences one can expect if exchange and correlation are taken into account. More information about the microscopic parameters of disorder can be obtained via the single-particle relaxation time, which can be determined with Shubnikov-de Haas measurements [1]. Measurements in a parallel magnetic field, where the 2DEG becomes spin-polarized [6], would be useful, as discussed in more detail in Ref.8.

4. Conclusions

We believe that thin AlAs quantum wells are very interesting because interface-roughness scattering is presumably the only relevant scattering mechanism. However, much more experimental work is necessary to study in detail the density dependence of the mobility near $N_{\text{MIT}}$ and also the temperature dependence of the mobility. We ask for systematic Shubnikov-de Haas measurements in order to determine the density dependence of the Dingle temperature and the effective electron mass.

References

[1] Ando T, Fowler A B and Stern F 1982 Rev. Mod. Phys. 54 437
[2] Drummond T J and Fritz I J 1985 Appl. Phys. Lett. 47 284
[3] Shayegan M, Poortere E P, Gunawan O, Shkolnikov Y P, Tutuc E and Vakili K 2006 Phys. Sta. Sol. (b) 243 3629
[4] Vakili K, Shkolnikov Y P, Tutuc E, De Poortere E P, Padmanaabhan M and Shayegan M 2006 Appl. Phys. Lett. 89 172118
[5] Vakili K, Shkolnikov Y P, Tutuc E, De Poortere E P and Shayegan M 2004 Phys. Rev. Lett. 92 226401
[6] Kravchenko S V and Sarachik M P 2004 Rep. Prog. Phys. 67 1; Shashkin A A 2005 Phys. Usp. 48 129
[7] Gold A 2007 Appl. Phys. Lett. 92 082111
[8] Gold A and Marty R 2007 J. Appl. Phys. 102 083705
[9] Gold A 1986 Solid State Commun. 60 531; Gold A 1987 Phys. Rev. B 35 723
[10] Gold A and Götte W 1986 Phys. Rev. B 33 2495
[11] Singwi K S and Tosi M P 1981 Solid State Phys. 36 177
[12] Gold A and Calmels L 1991 Phys. Rev. B 48 11622; Gold A 1997 Z. Phys. B 103 491
[13] Dolgopolov V T, Deviatov E V, Shashkin A A, Wieser U, Kunze U, Abstreiter G, Brunner K 2003 Superlattices and Microstructures 33 271
[14] Gold A 1989 Appl. Phys. Lett. 54 2100; Gold A 1991 Phys. Rev. B 44 8818