Metal-insulator transition in silicon MOSFETs: new viewpoint

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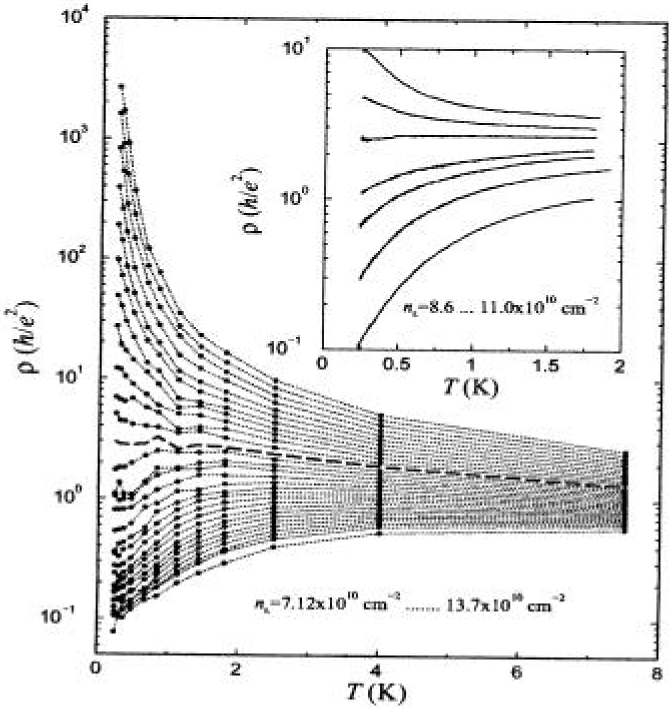
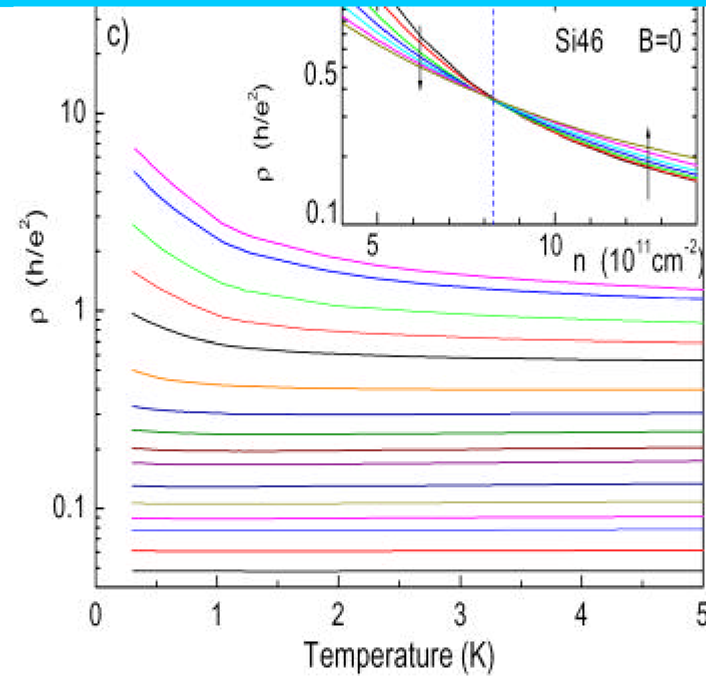
Unexpected s(T) behavior. MIT as a quantum phase transition.

E. Abrahams, S.V. Kravchenko, M.P. Sarachik, Rev. Mod. Phys., 73, 251 (2001).





From V.M. Pudalov et al., cond-mat/0103087.

Temperature dependence of the resistivity in a dilute low-disordered Si MOSFET.
(from Kravchenko et al., 1995)

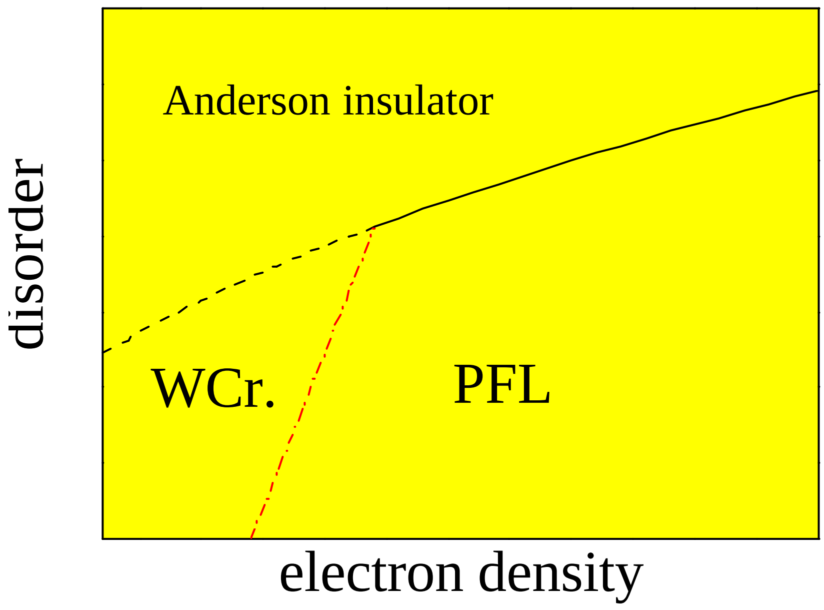
Every crossing of $\rho(n_s, T)$ curves was regarded as evidence for a very similar phase transition.

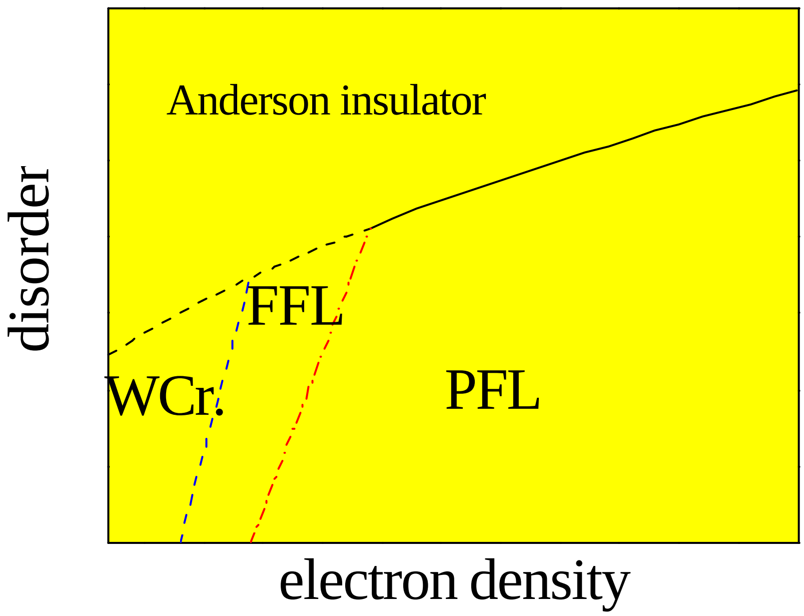
This idea is wrong!

Phase diagrams.

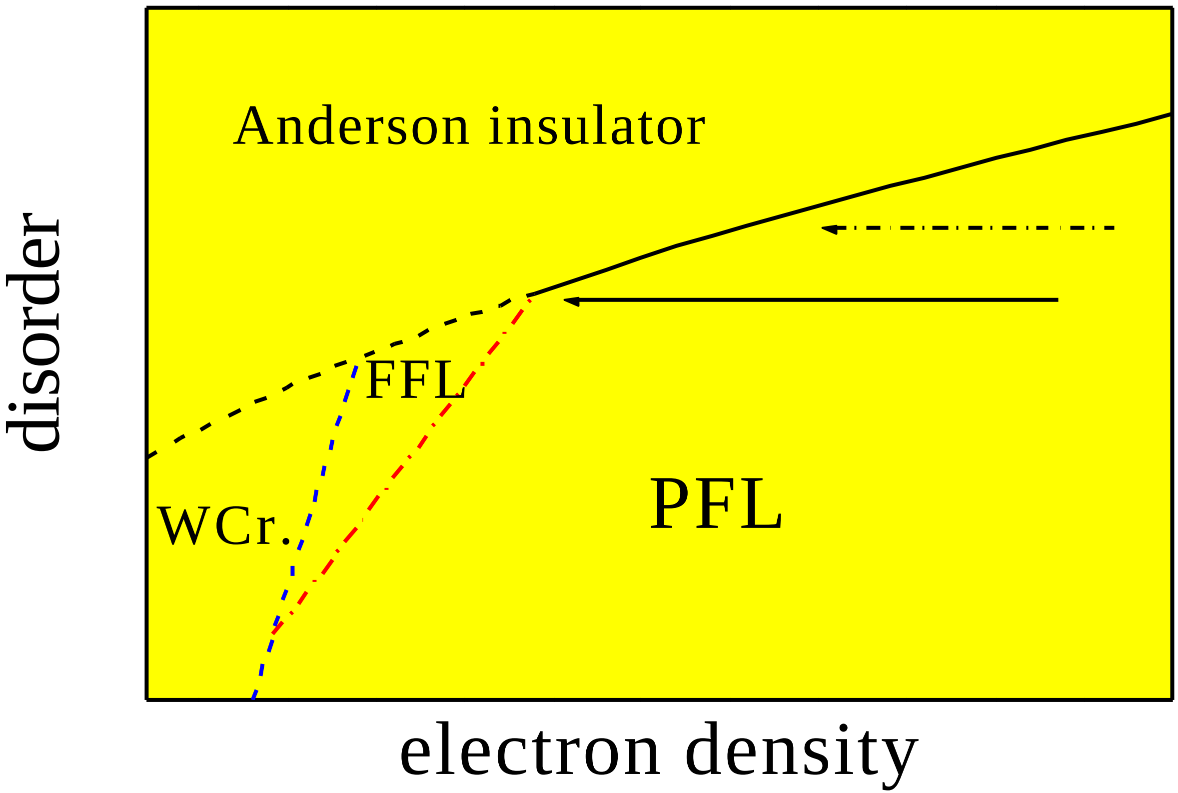
B.Tanatar and D.M. Ceperley,
Phys.Rev., **39**, 5005 (1989).

C.Attaccalite et al.
Phys.Rev. Lett., 88, 256601 (2002)





Phase diagrams.



M. Nita et al.
Cond-mat/ 0304360.

- If we want to get information about "clean" 2D system, we need to investigate properties of the liquid phase.
- At present, we have the following information:
- (1) $p_F \propto n_s^{1/2}$ (Theory: M.A. Khodas and A.M Finkel'stein, cond-mat/02312628, experiment: A.A. Shashkin et al., Phys. Rev. Lett., **87**, 086801 (2001).
- (2) $v_F \rightarrow 0$ at $n_s \rightarrow n_c$!!(?) (A.A. Shashkin et al., Phys.Rev.B, **66**, 073303 (2002), cond-mat/0301187.)

  It means that $\chi^{-1} \rightarrow 0$ at $n_s \rightarrow n_c$!!(?) (A.A. Shashkin et al., Phys. Rev.Lett., **87**, 086801 (2001), V.M Pudalov et al., Phys. Rev. Lett., **88**, 196404 (2002), S.V. Kravchenko et al., Phys. Rev. Lett., **89**, 219701 (2002)).
- (3) τ and T_D have weak density dependence near n_c (A.A. Shashkin et al., Phys.Rev.B, **66**, 073303 (2002), cond-mat/0301187.)
- (4) $p_F(P=0)/v_F(P=0) = p_F(P=1)/v_F(P=1)$;

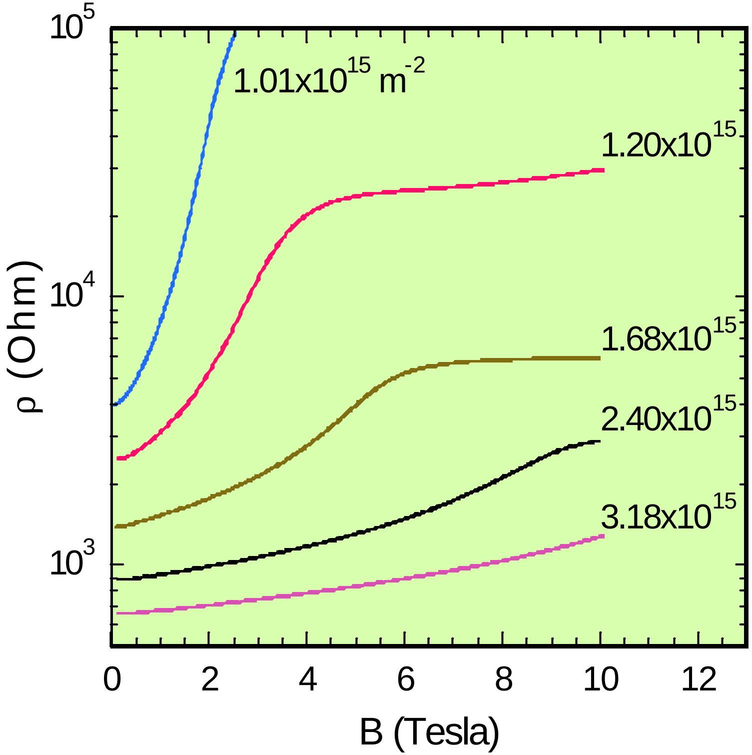
  $p_F(P=1) = \sqrt{2}\, p_F(P=0)$.

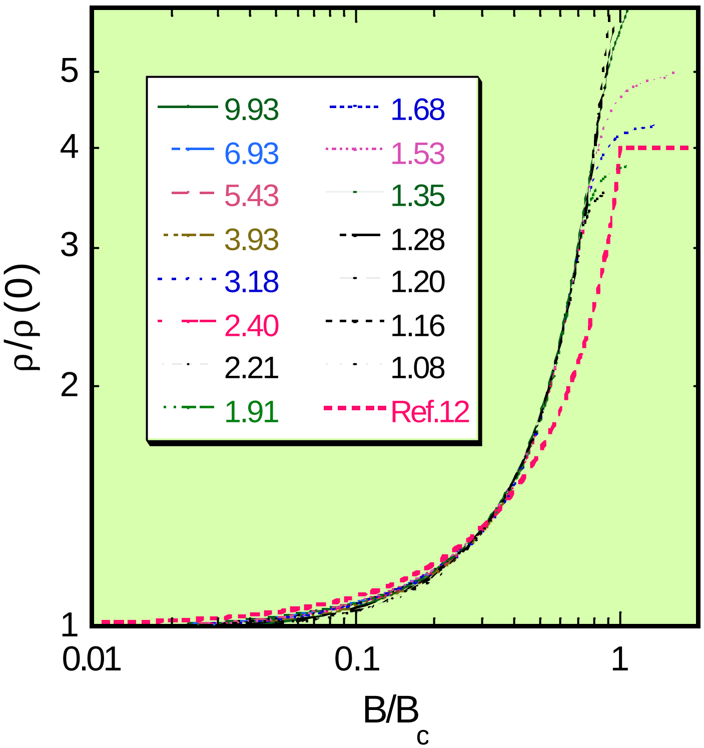
  (A.A. Shashkin et al., cond-mat/0301187.)
- (5) $dn_s/d\varepsilon|\varepsilon_F =$????

Magnetoresistance in a parallel magnetic field.

A.A. Shashkin, S.V. Kravchenko. V.T. Dolgopolov, and T.M. Klapwijk, PRL 87, 086801 (2001).

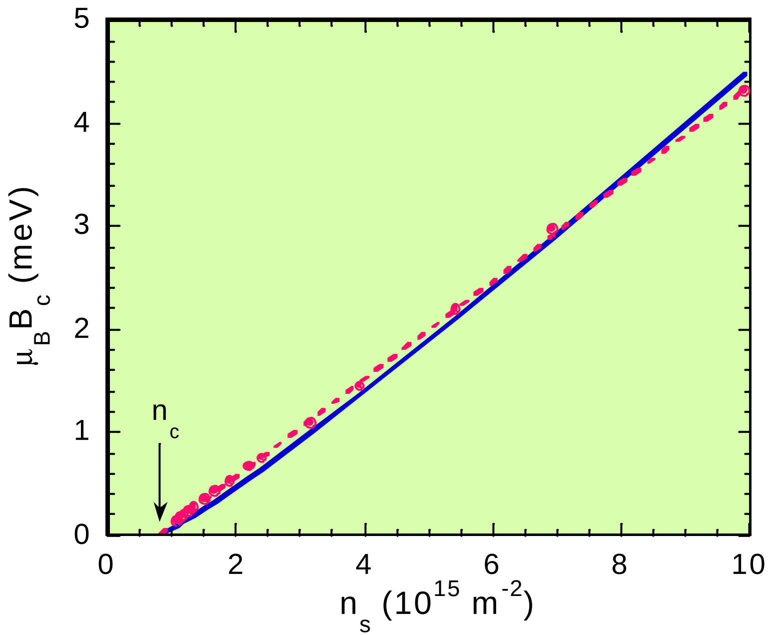
V.T. Dolgopolov and A. Gold, JETP Lett, 71, 27 (2000)





Critical magnetic field as a function of electron density.

A.A. Shashkin, S.V. Kravchenko. V.T. Dolgopolov, and T.M. Klapwijk, PRL 87, 086801 (2001).



$B_c \rightarrow 0$ at $n_s \rightarrow n_c$.

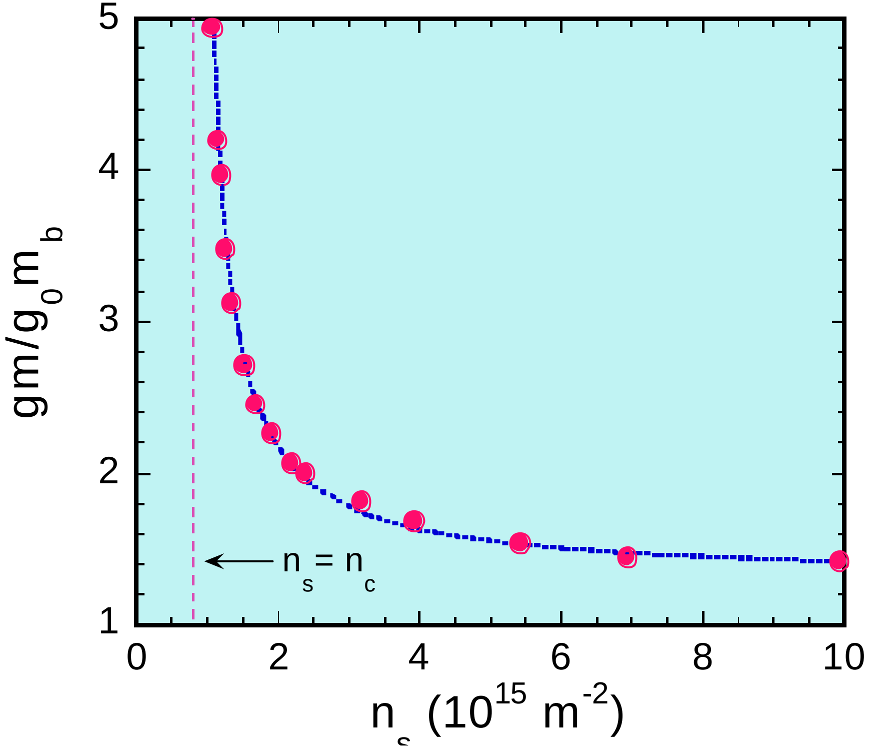
$\langle \chi^{-1} \rangle = B_c/(1/2\, \mu_B g_0 n_s) \rightarrow 0$.

$\chi^{-1}(P=0) \rightarrow 0$.

Only the last equation is necessary to conclude that the effective mass strongly increases near the critical electron density.

gm as a function of electron density.

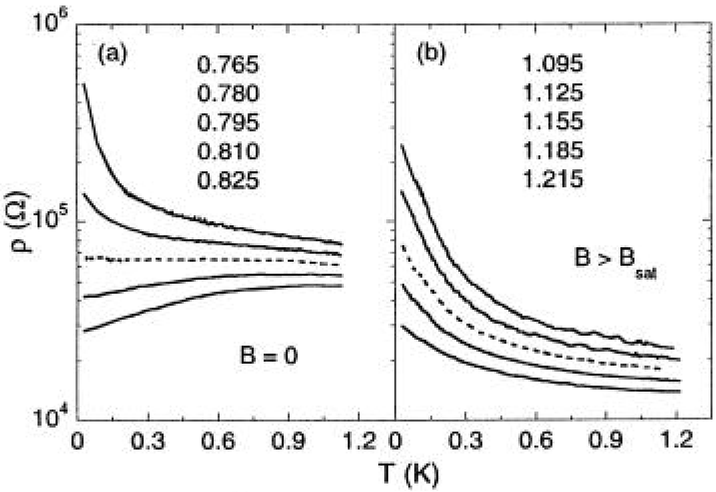
A.A. Shashkin, S.V. Kravchenko. V.T. Dolgopolov, and T.M. Klapwijk, PRL 87, 086801 (2001).

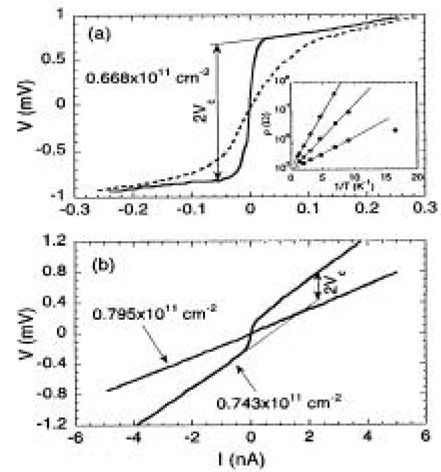


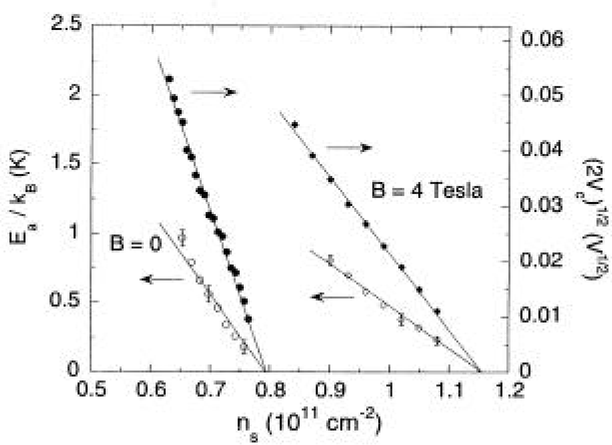
To extract *m* and *g*, we assume that $\chi^{-1}(P=0) = \langle\chi^{-1}\rangle$.
This relation is exact at $n_s >> n_c$.
The validity of this relation in the vicinity of n_c will be experimentally proven below.

How to find n_c experimentally?

A.A. Shashkin, S.V. Kravchenko, and T.M Klapwijk, PRL, **87,** 266402 (2001).





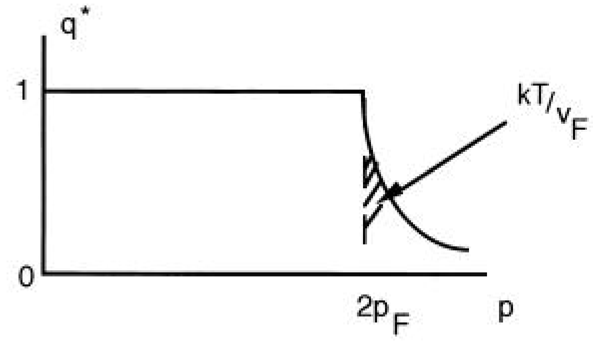


All used methods give the same value of n_c.

Temperature dependence of conductivity.

A.Gold, V.T. Dolgopolov,
PRB 33, 1076 (1986).

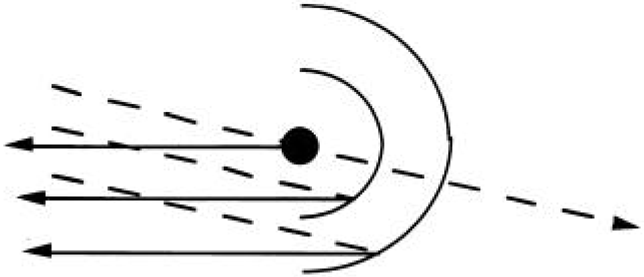
$$\Delta\sigma/\sigma = -kT/E_F\, C(n_s)$$



G. Zala, B. Narozhny, I.L. Aleiner
PRB 64,214404(2001).

$$\Delta\sigma/\sigma = kT/E_F\,(1+7F_0^{\sigma}(1+F_0^{\sigma})^{-1})$$

$$g = 2\,(1+F_0^{\sigma})^{-1}$$



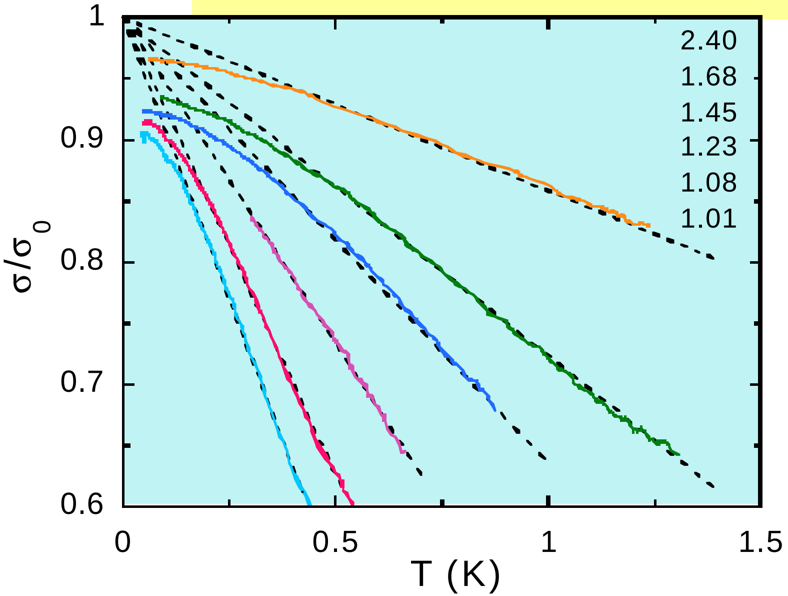
Temperature dependence of conductivity.

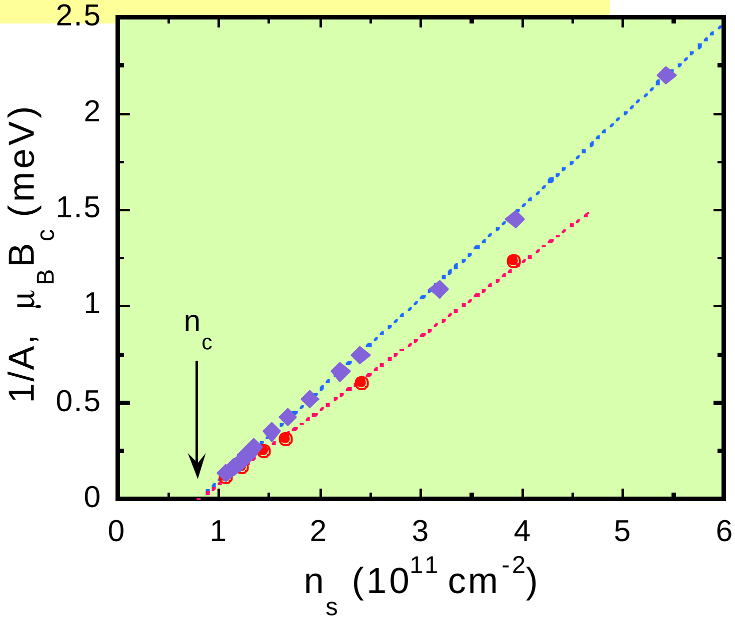
A.A. Shashkin, S.V. Kravchenko, V.T. Dolgopolov, and T.M. Klapwijk, PRB, 66, 073303 (2002)

$\sigma(T)/\sigma=1-AkT$, $gm = \pi?^2 n_s/(B_c\mu_B)$; $A= -(1+\alpha F_0^\sigma)gm/(\pi?^2 n_s)$

$A= -(1+\alpha F_0^\sigma)/(B_c\mu_B)$.

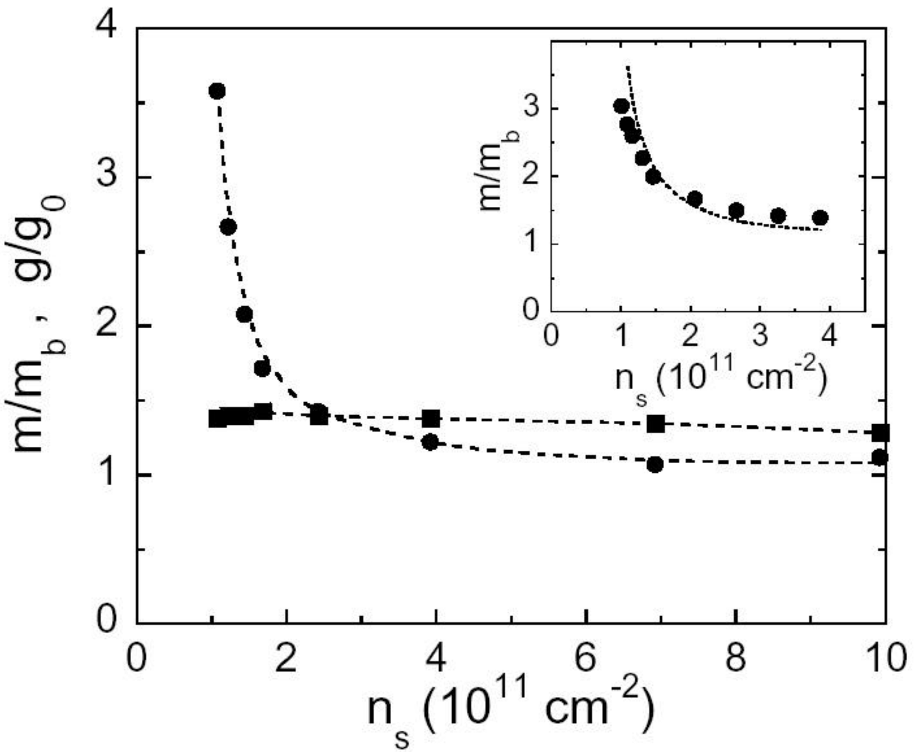
According to experiment, $A^{-1} \propto B_c$, which means $g(n_s)$=const. The last conclusion is independent of the value of α and of the accuracy of B_c determination.

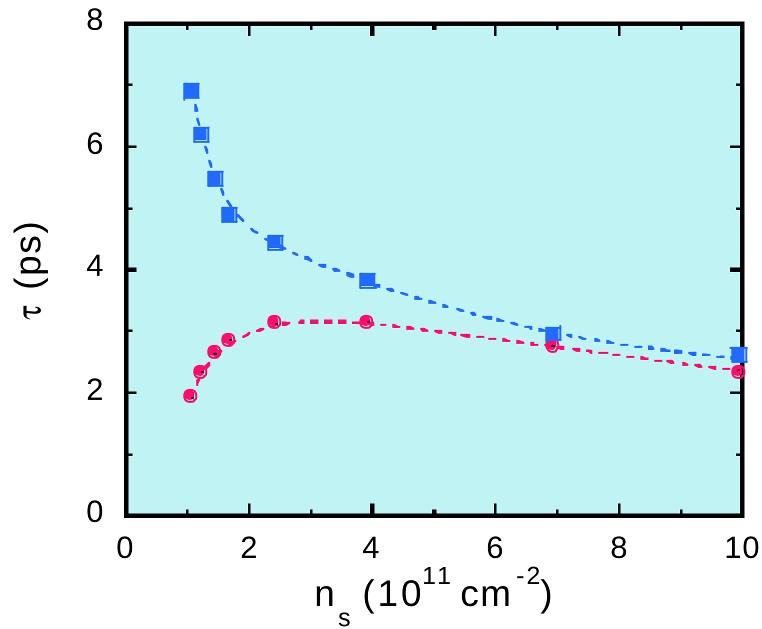




Sharp increase of the effective mass near the critical density in a metallic 2D electron system.

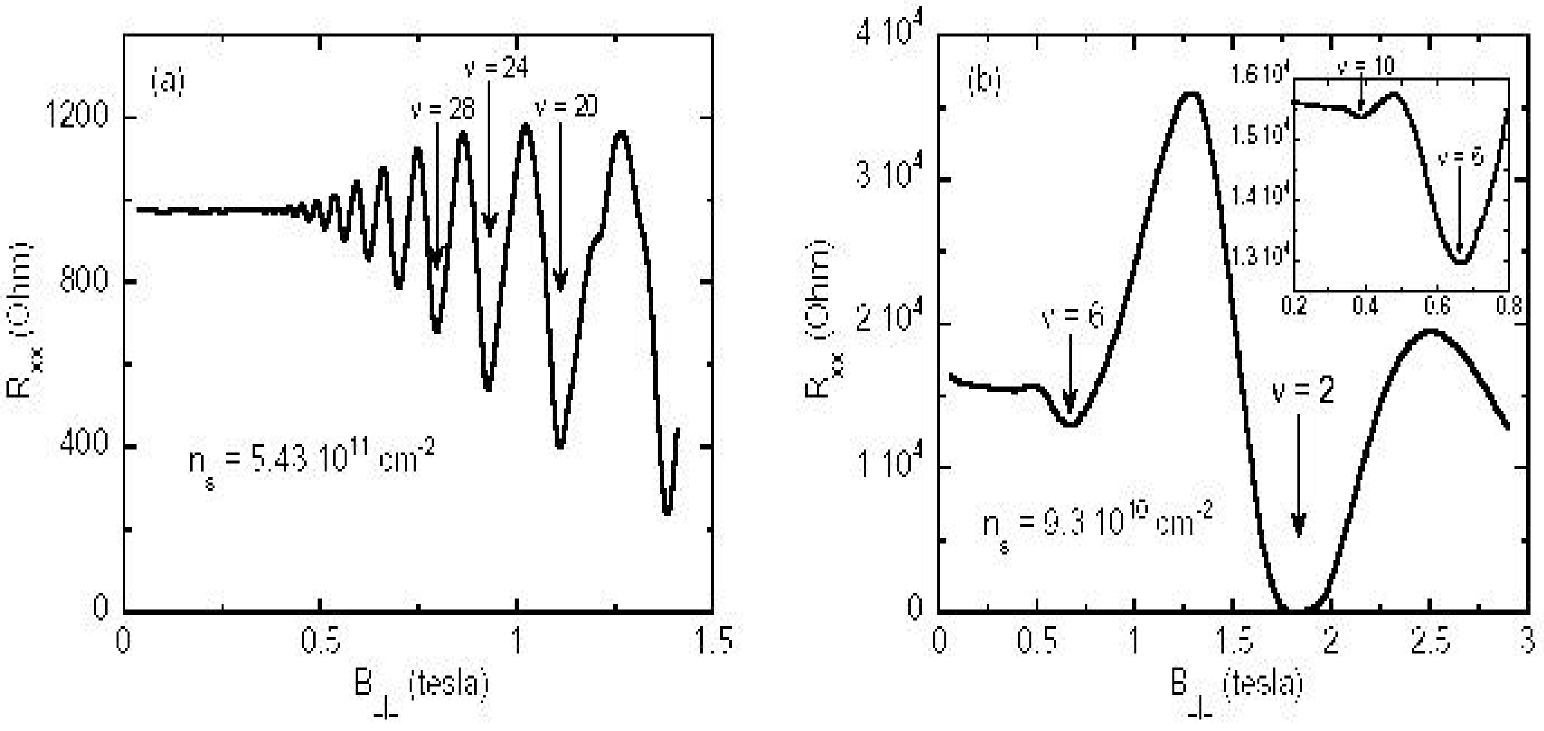
A.A. Shashkin, S.V. Kravchenko, V.T. Dolgopolov, and T.M. Klapwijk, PRB, 66, 073303 (2002)





Shubnikov-de Haas oscillations at T=40mK.

A.A. Shashkin, S.V. Kravchenko, V.T. Dolgopolov and T.M. Klapwijk, cond-mat/ 0302004

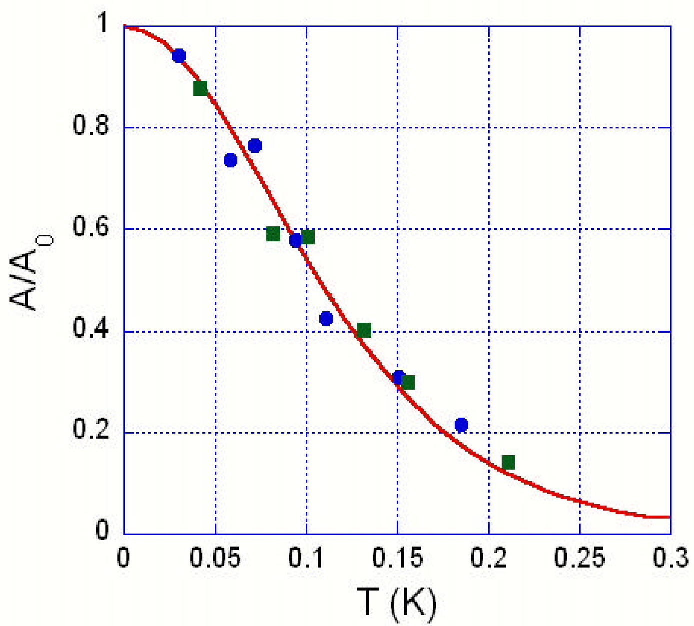


Amplitude of the weak-field SdH oscillations vs. temperature at $n_s = 1.17 \cdot 10^{11}$ cm^{-2}.

A.A. Shashkin, M. Rahimi, S. Anissimova, S.V. Kravchenko, V.T. Dolgopolov, T.M. Klapwijk, cond-mat/ 0301187.

$$A(T) = A_0 \frac{2\pi^2 k_B T/\hbar\Omega_c}{\sinh(2\pi^2 k_B T/\hbar\Omega_c)},$$

where $A_0 = 4\exp(-2\pi^2 k_B T_D/\hbar\Omega_c)$ and T_D is the Dingle temperature.

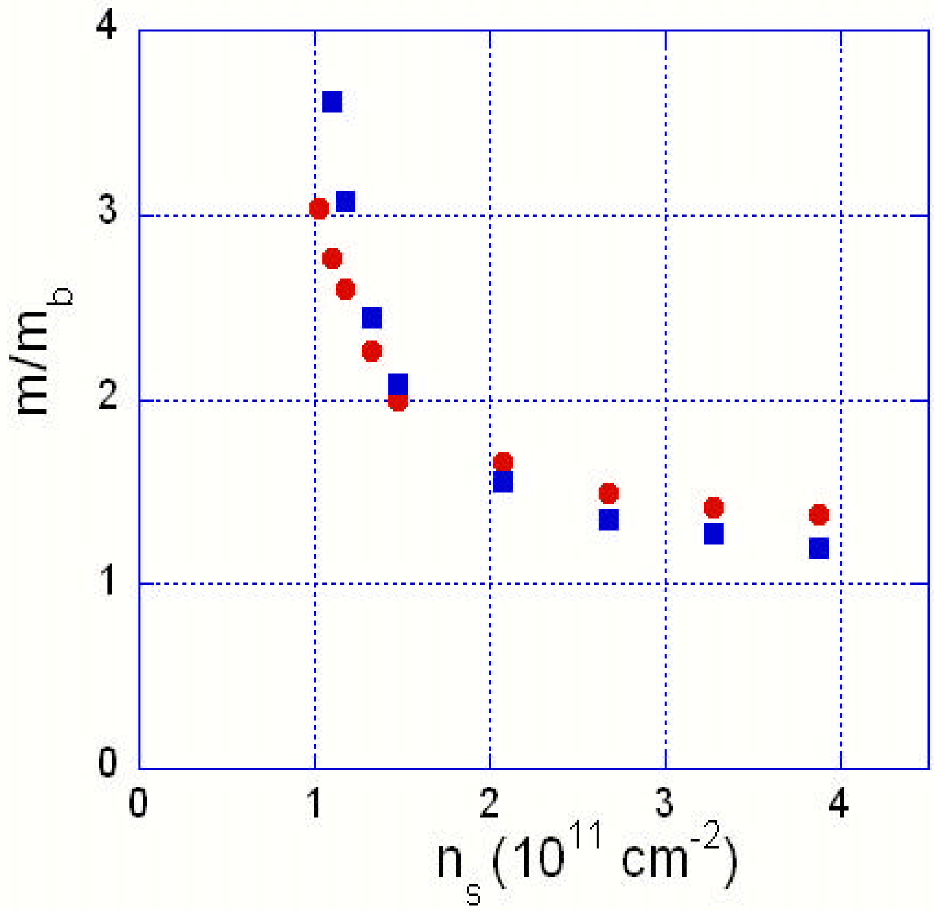


Oscillations numbers: ν=10 (dots) and ν=14 (squares). The value of T for the ν =10 data is divided by the factor of 1.4.

The amplitude of the SdH oscillations follows the calculated curve down to the lowest achieved temperature. The electrons are in a good thermal contact with the bath.

Comparison of the effective mass received by two different experimental methods.

A.A. Shashkin, M. Rahimi, S. Anissimova, S.V. Kravchenko, V.T. Dolgopolov, T.M. Klapwijk, cond-mat/ 0301187.

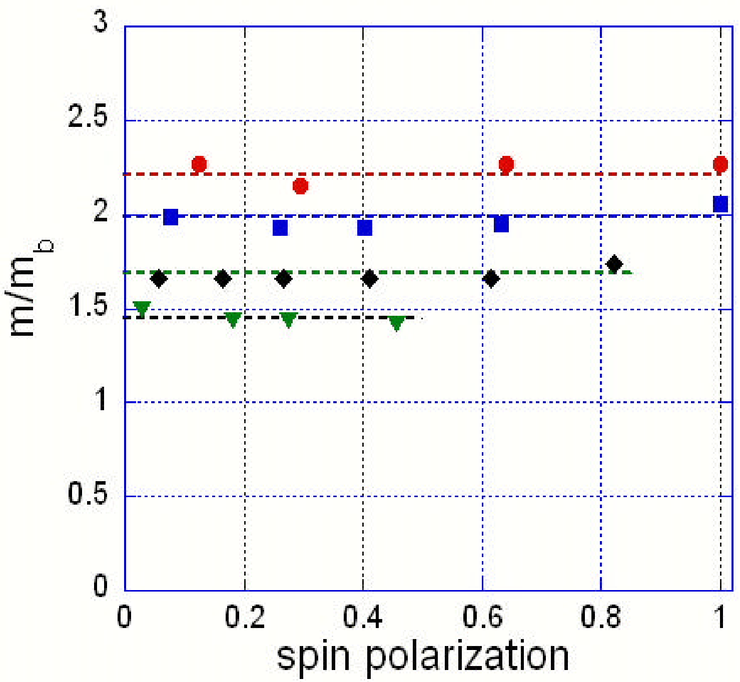


The effective mass determined from the analysis of the parallel field magnetoresistance and temperature dependent conductivity (squares) in comparison to the one extracted from the analysis of SdH oscillations (circles).

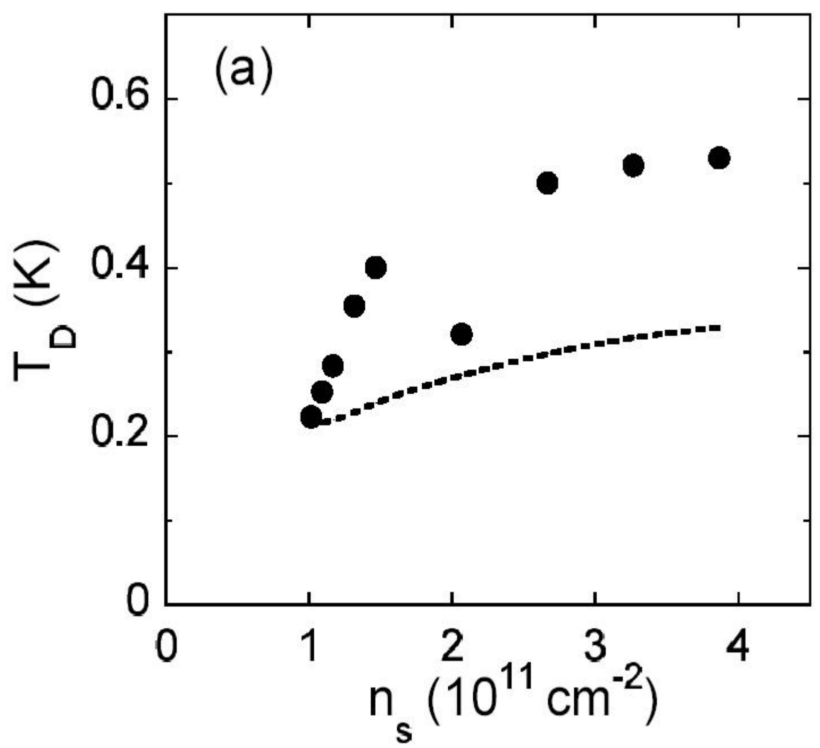
The agreement (within experimental accuracy) between the results obtained by two independent methods adds confidence in our results and conclusions

The effective mass as a function of the degree of spin polarization..
A.A. Shashkin, M. Rahimi, S. Anissimova, S.V. Kravchenko, V.T. Dolgopolov, T.M. Klapwijk, cond-mat/ 0301187.

Electron densities are:
1.32 , 1.47, 2.07, 2.67*
10^{11} cm $^{-2}$.



Dingle temperature extracted from SdH oscillations (dots) and that calculated from the transport scattering time (dashed line).



The electrons in GaAs/AlGaAs heterostructure.

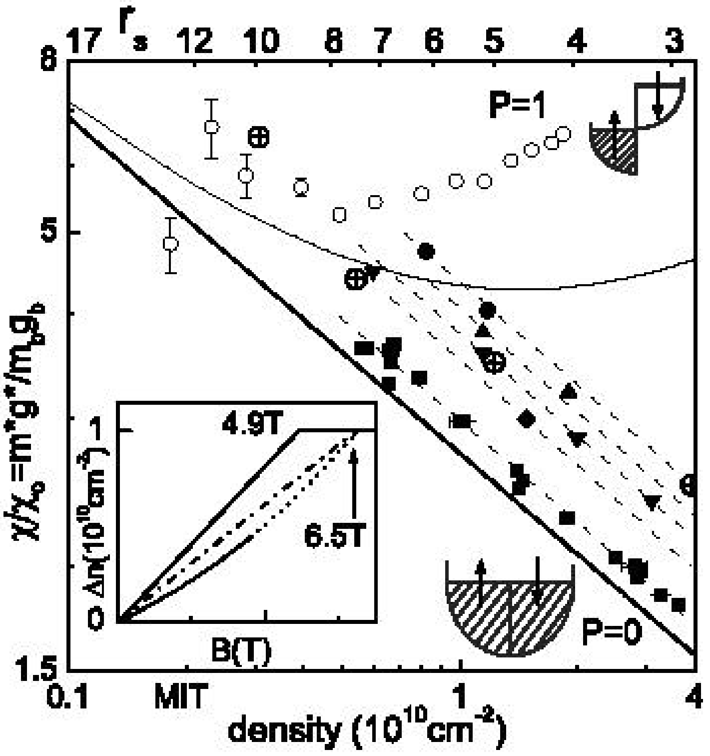
In comparison to the Si-MOSFET:

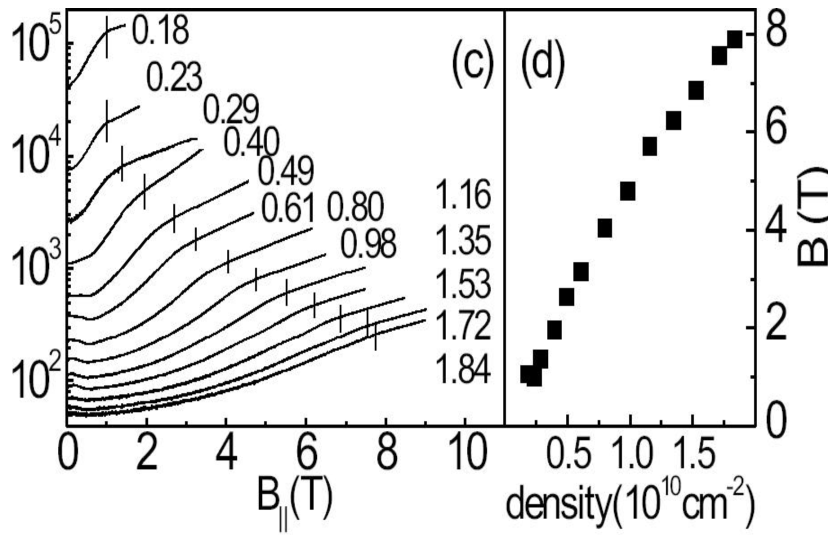
- absence of the valley splitting,
- smaller effective mass,
- higher value of ε_0 ,
- wide electron density distribution in Z – direction.

As a result, at a fixed electron density, the ratio E_C/E_F in GaAs/AlGaAs is at least 10 times smaller than that in Si-MOSFET. Electron density should be ~100 times smaller: $n_s < 2*10^9$ cm^{-2}.

J. Zhu, H.L.Stormer, L.N. Pfeiffer, K.W. Baldwin, and K.W. West
PRL, **90**, 056805 (2003)

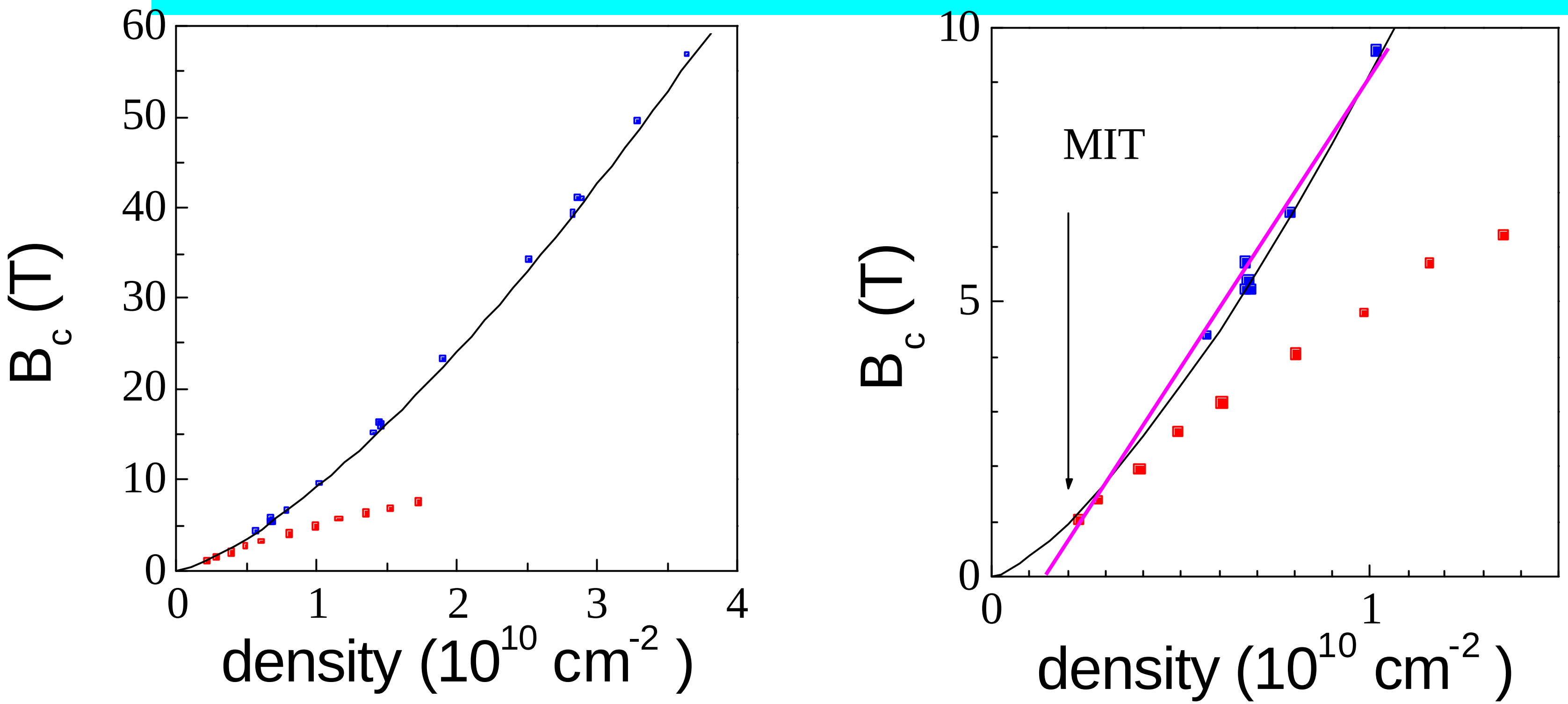
Heterostructure GaAs/AlGaAs, 2 DEG





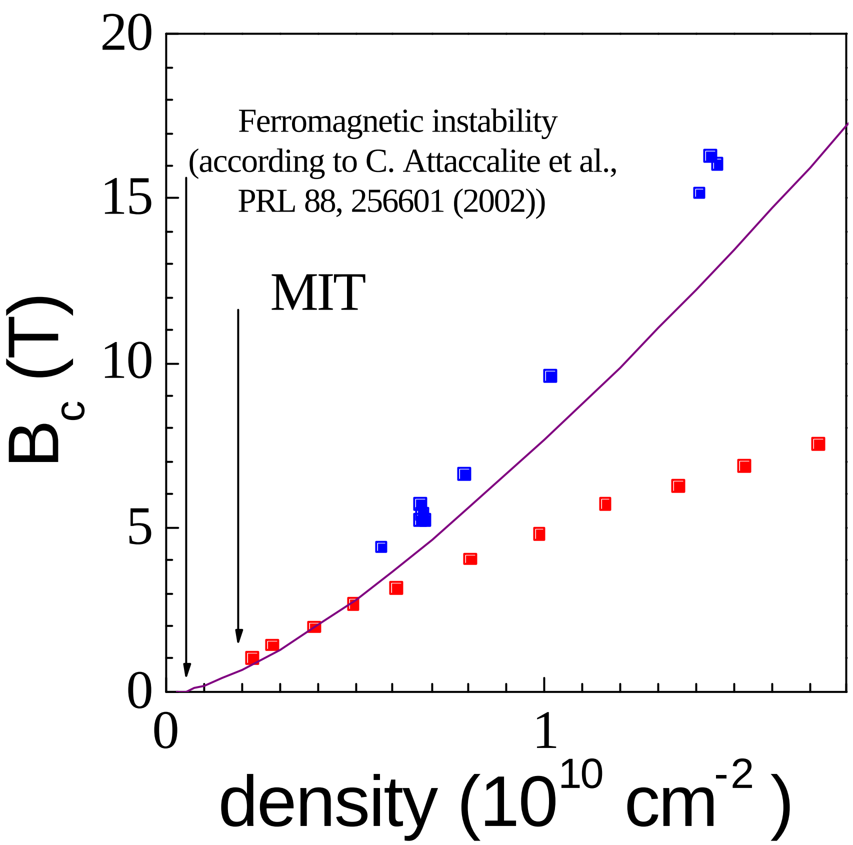
m^*g^*/m_bg_b obtained from SdH oscillations and from resistance saturation.

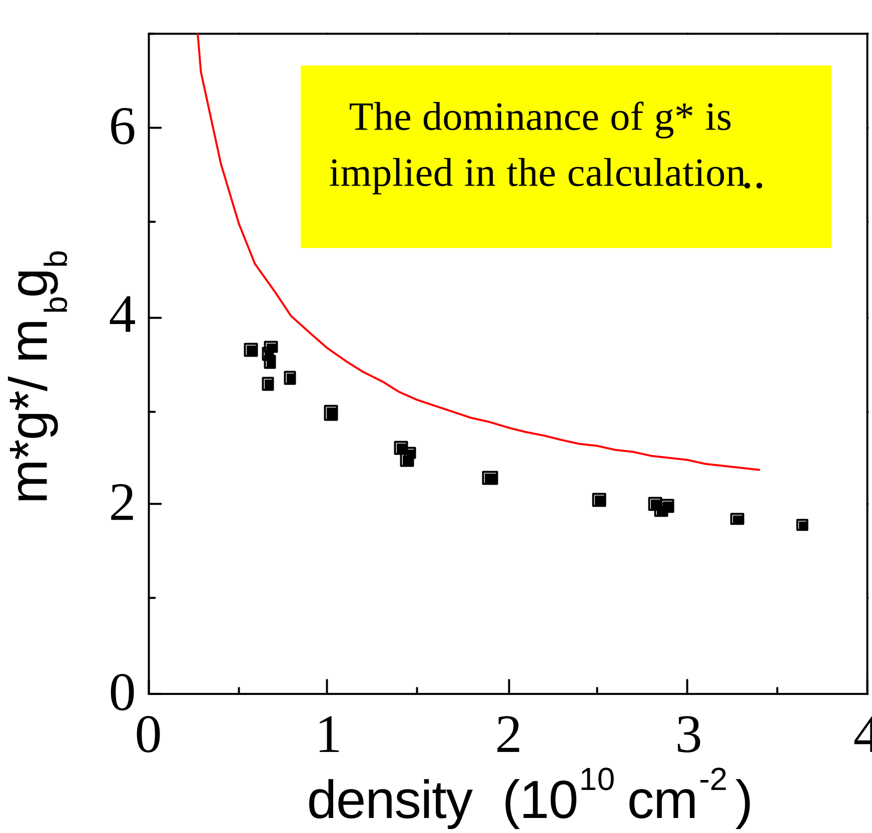
J. Zhu, H.L.Stormer, L.N. Pfeiffer, K.W. Baldwin, and K.W. West
PRL, **90**, 056805 (2003)



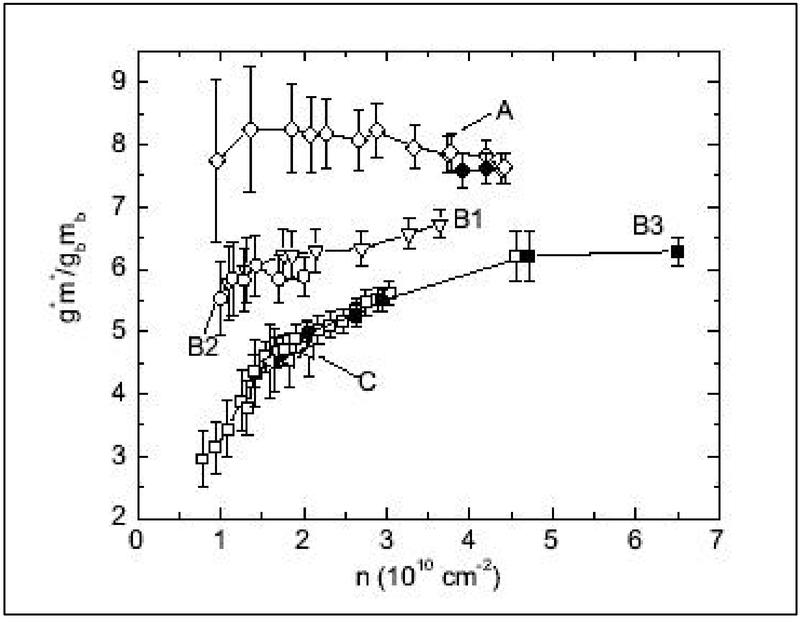
Whether it is possible to distinguish between the authors' fit through (0,0) point and the straight line?

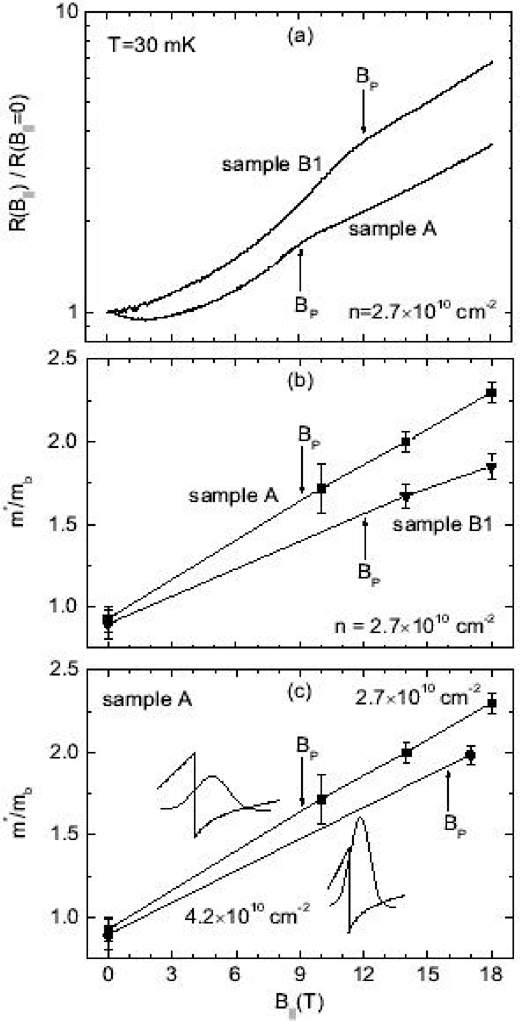
Comparison with the theory.





E. Tutic, S. Melinte, E.P. De Poortere, M. Shayegan, and R. Winkler

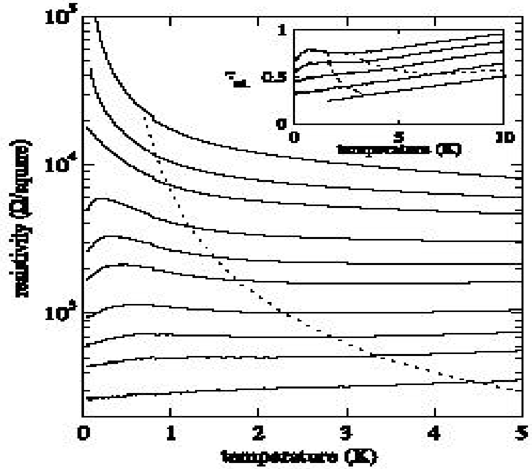


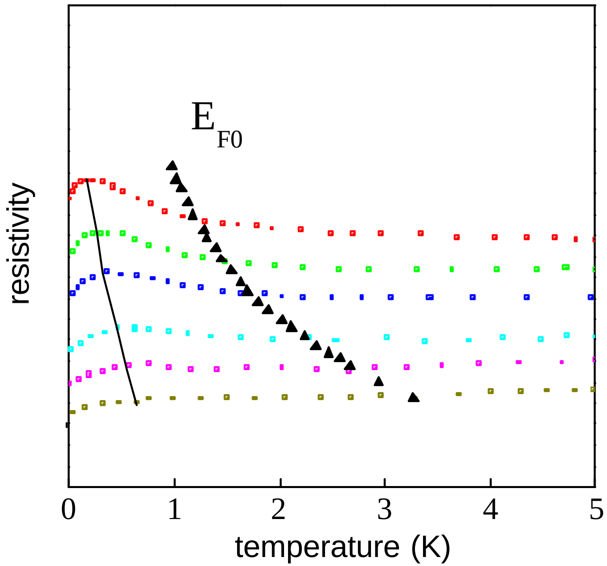


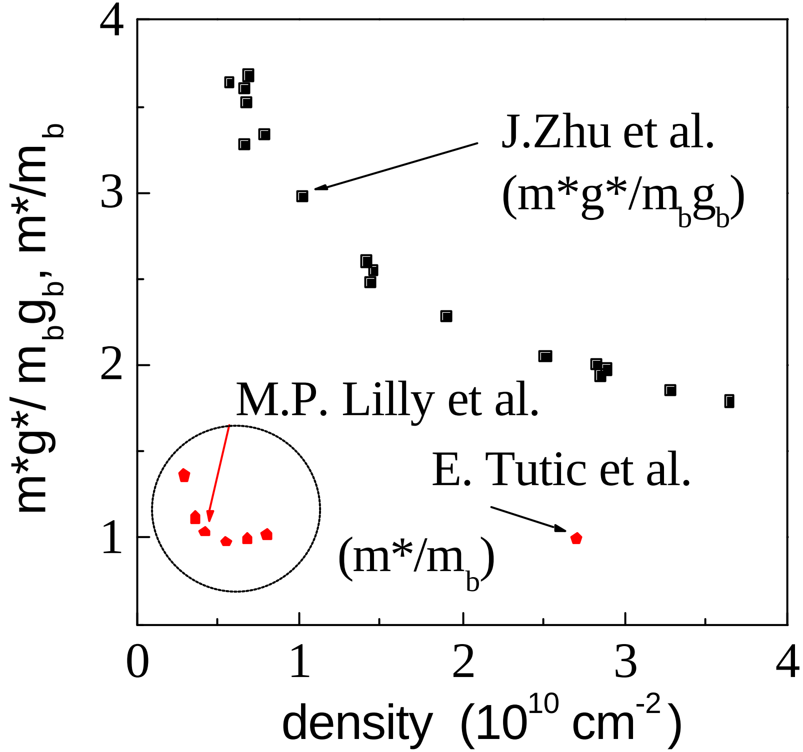
g^*m^*/gm is strongly sample dependent, signaling that the orbital effects are the origin for the enhanced m*.

The effective mass $m^* = m_b$ for electron densities $2.7 * 10^{10} < n_s < 4.2 * 10^{10}$ cm^{-2}.

Evaluation of the effective mass based on results of cond-mat/0210155 (Lilly et al.).







- Weak increase of g* with decreasing electron density is consistent with Si-MOSFET results.

- Electron densities under investigation are still too high.

- MIT, observed at $n_s \geq 2*10^9$ cm^{-2}, is conventional Anderson transition.

- Data for m* at lowest electron density are necessary (e.g. SdH measurements).

Conclusion.

(i) We have found that different experimental methods give strong evidence for a sharp increase of the effective mass with decreasing electron density, while the *g* –factor remains nearly constant.

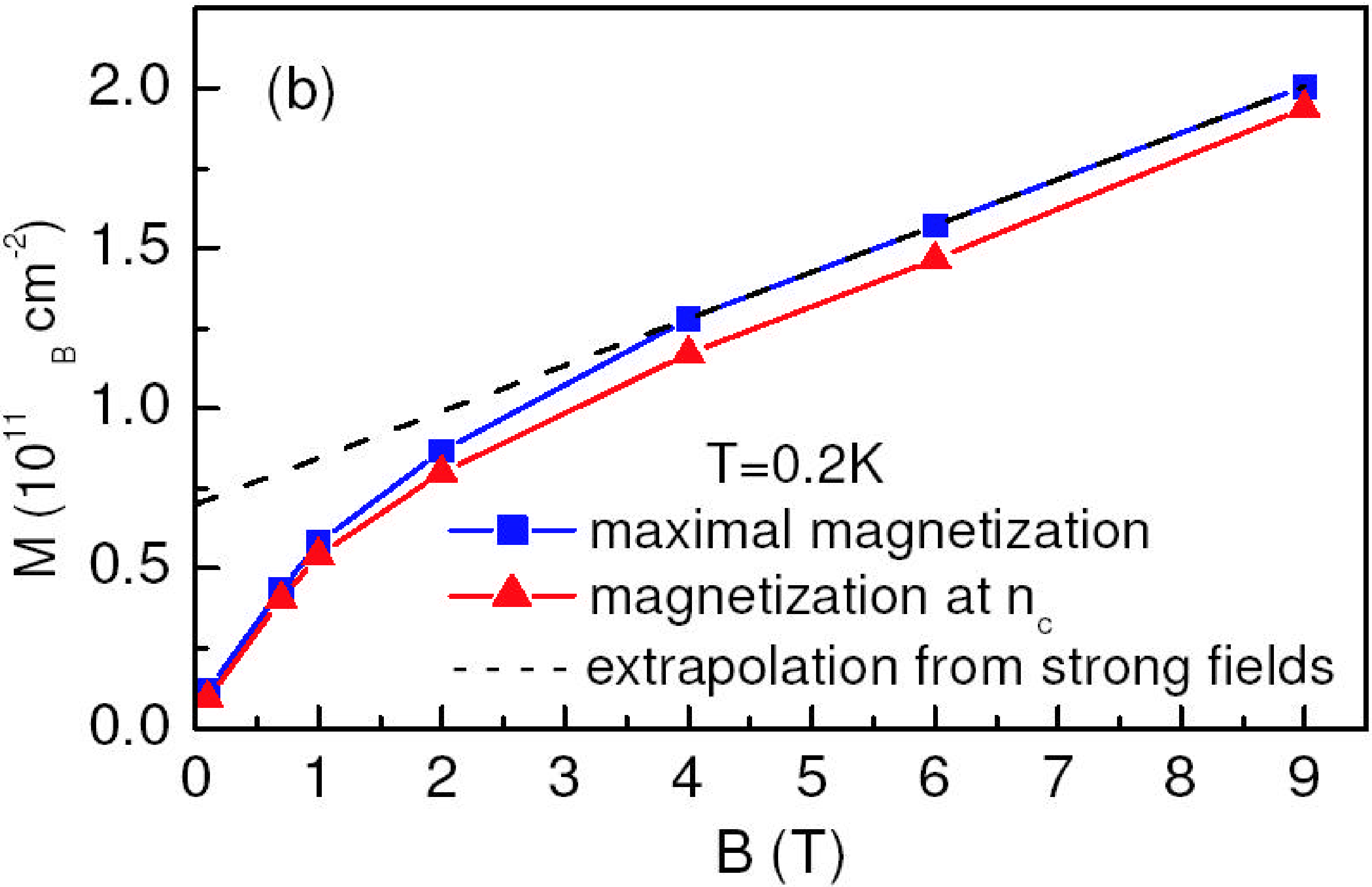
(ii) The corresponding strong rise of the spin susceptibility $\chi \propto gm$ may be a precursor of a spontaneous spin polarization; unlike in the Stoner scenario, it originates from the enhanced effective mass rather than from the increase of *g*-factor.

(iii) By studying Shubnikov-de Haas oscillations in tilted magnetic fields, we have found that the enhanced effective mass is independent of the degree of spin polarization and, therefore, its increase is not related to spin exchange effects.

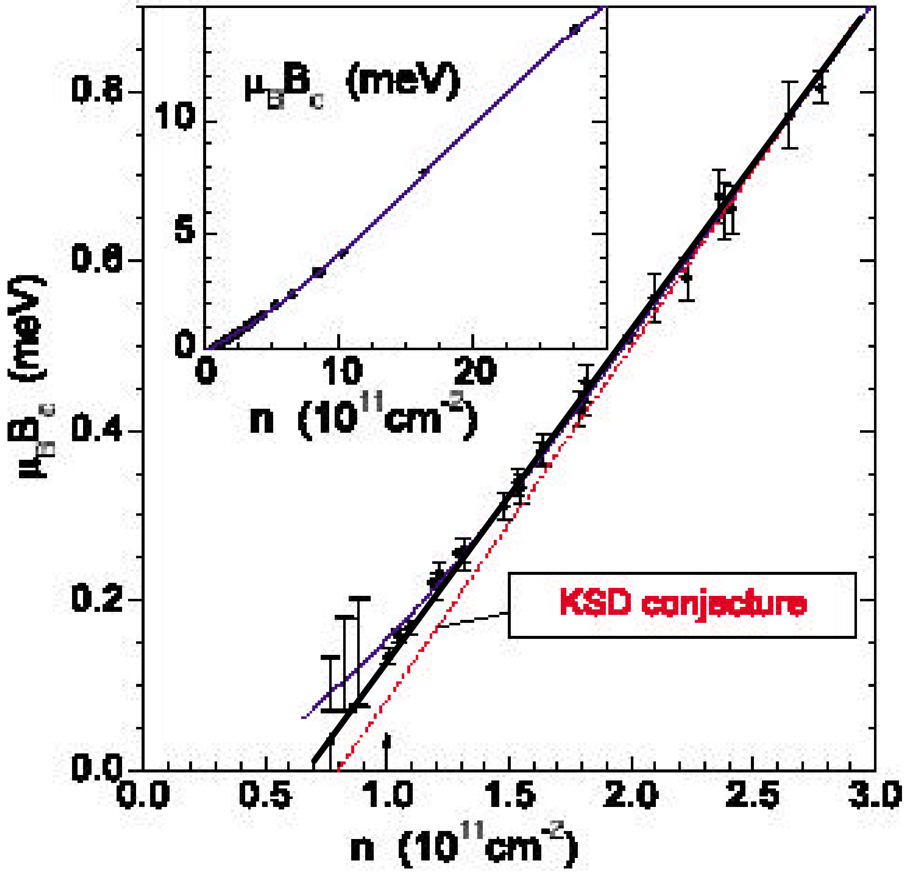
(iv) We conclude that the dilute 2D electron system in silicon behaves well beyond a weakly interacting Fermi liquid and that the metal-insulator transition point in best samples practically coincides with some quantum phase transition, which is not a disorder driven transition.

Thermodynamic spin magnetization of strongly correlated two-dimensional electrons in a silicon inversion layer.
O.Prus et al., PRB **67**, 205407 (2003).

Exp = D+M; D = Exp-SdH: M = Exp-D = SdH!

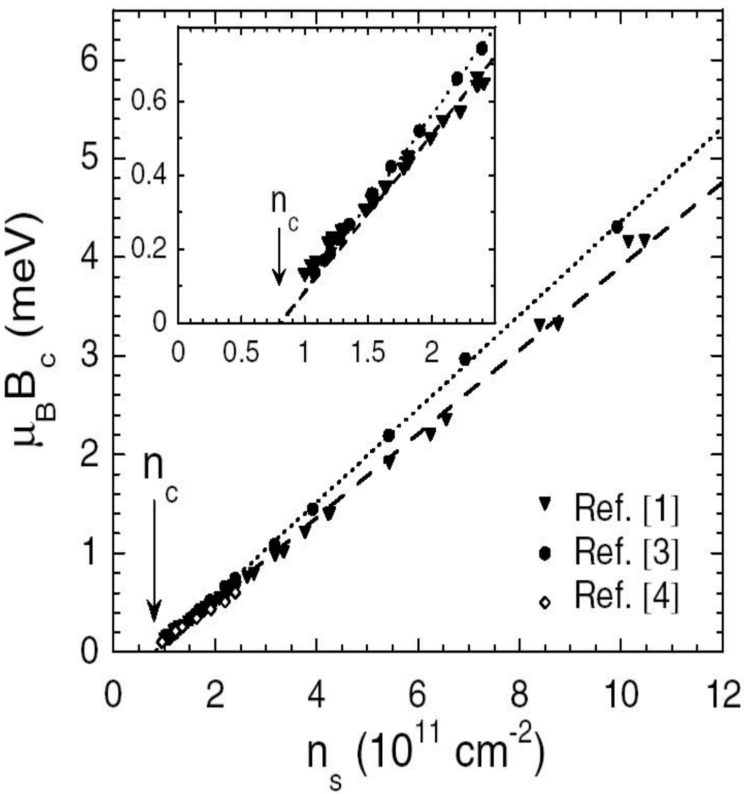


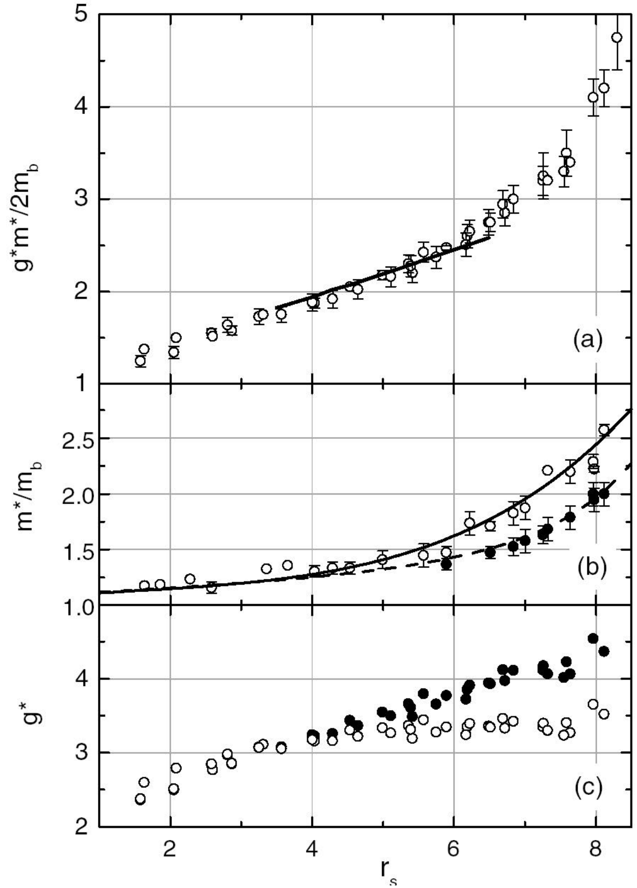
Pudalov V.M.et al., Phys. Rev. Lett. 89, 219702 (2002)



"We determined the spin susceptibility χ^*, the effective mass m^*, and the g^* factor for mobile electrons. These quantities increase gradually with decreasing density."

Pudalov V.M. et al., Phys. Rev. Lett., **88**, 196404 (2002).





“[19] Below 0.3 K, we observed the trend of simultaneous saturation of the temperature dependences of ρ_0, $d\rho_{xx}$, and the dephasing rate, which is presumably caused by electron overheating.”