Electron-electron interaction in one- and two-dimensional ferromagnetic (Ga,Mn)As

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We investigated the magnetotransport in high quality ferromagnetic (Ga,Mn)As films and wires. At low temperature the conductivity decreases with decreasing temperature without saturation down to 20 mK. Here we show that the conductivity decrease follows a \( \ln(T/T_0) \) dependency in two-dimensional films and a \(-1/\sqrt{T}\) dependency in one-dimensional wires and is independent of an applied magnetic field. This behavior can be explained by the theory of electron-electron interaction.

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Up to now the ferromagnetic semiconductor (Ga,Mn)As (Ref. 1) is one of the best understood ferromagnetic semiconductors and has become a promising candidate for future spintronic devices. The Mn ions substituting Ga on the regular sites of the zinc-blende lattice provide both holes and magnetic moments. The ferromagnetic order between the individual Mn ions is mediated by these holes.\(^2\) Ferromagnetism in (Ga,Mn)As is well understood, allowing to predict Curie temperature,\(^2\) magnetocrystalline anisotropies,\(^3\) as well as anisotropic magnetoresistance effects.\(^4\) However, the temperature dependence of the conductivity of (Ga,Mn)As is still under debate. Starting at room temperature the conductivity decreases with decreasing temperature until a local minimum is reached around the Curie temperature. Attempts to explain this minimum include, e.g., the formation of magnetic polarons,\(^5,6\) or an interplay with universal conductance fluctuations.\(^7\) A recent work\(^8\) explains the temperature-dependent conductivity above and below \(T_C\) within a picture invoking localization effects using an extended version of the scaling theory of Abrahams \textit{et al.}\(^9,10\) At temperatures below \(T_C\) the conductivity increases again in metallic samples, reaches a local maximum at about 10 K before it drops again for decreasing temperatures. The temperature dependence in this low-temperature regime is the focus of the present Rapid Communication. Attempts to explain this behavior are, e.g., based on Kondo scattering,\(^11\) weak localization,\(^12\) or Mott hopping.\(^13\) A very recent report investigating three-dimensional (3D) (Ga,Mn)As films ascribes the conductivity decrease to Aronov-Altshuler scaling in 3D.\(^14\) By using one-dimensional (1D) and two-dimensional (2D) samples we show below that the decreasing conductivity in this regime can be ascribed to electron-electron interaction (EEI). The effect of electron-electron interaction arises from a modified screening of the Coulomb potential due to the diffusive propagation.\(^15\) The expected temperature dependence of the conductivity change for EEI depends on the dimensionality and goes with \(\ln(T/T_0)\) for 2D samples and with \(-1/\sqrt{T}\) for 1D samples. This behavior has been found in our experiments.

For the experiment we used three different (Ga,Mn)As wafers, labeled 1–3 (see Table I), grown by low-temperature molecular beam epitaxy on semi-insulating GaAs.\(^16\) The nominal Mn concentration of the (Ga,Mn)As layers varied between 4% and 5.5% with corresponding Curie temperatures between 90 and 150 K. To investigate the transport properties of two- and one-dimensional (Ga,Mn)As devices we fabricated Hall bars and arrays of wires using optical lithography, e-beam lithography, and subsequent reactive ion etching. Arrays of wires were used to suppress universal conductance fluctuations by ensemble averaging. Au contacts to the devices were made by lift-off technique. The relevant parameters of the investigated samples are listed in Table I. Magnetotransport measurements were carried out in a top-loading dilution refrigerator with a base temperature of 15 mK using standard four-probe lock-in techniques. Small measuring currents (25 pA to 1 nA) were used to avoid heating.

To investigate magnetotransport at millidegrees Kelvin temperatures, we measured the resistance of quasi-2D films and quasi-1D wires in a perpendicular applied magnetic field. According to Lee and Ramakrishnan\(^15\) a (Ga,Mn)As film is considered to be 2D in the context of electron-electron interactions if the film thickness \(t\) is smaller than the thermal diffusion length \(l_T=\sqrt{\hbar D/k_B T}\). For our samples \(l_T\) is \(\sim 200\) nm at 20 mK. Similarly, a sample is one dimensional if both wire width \(w\) and the wire thickness \(t\) are smaller than \(l_T\).

We start with discussing temperature-dependent transport.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Sample & \(1_{2D}\) & \(1_{2D}\) & \(2_{2D}\) & \(3_{2D}\) & \(1_{1D}\) & \(1_{1D}\) & \(1_{1D}\) \\
\hline
\(l\) (\(\mu m\)) & 180 & 180 & 60 & 180 & 7.5 & 7.5 & 7.5 \\
\(w\) (\(\mu m\)) & 11 & 11 & 7.2 & 10 & 0.042 & 0.042 & 0.035 \\
\(t\) (nm) & 42 & 42 & 20 & 50 & 42 & 42 & 42 \\
\(N\) & 1 & 1 & 1 & 1 & 25 & 25 & 12 \\
\(a\) (hours) & 0 & 51 & 8.5 & 0 & 0 & 51 & 0 \\
\(T_C\) (K) & 90 & 150 & 95 & 90 & 90 & 150 & 90 \\
\(p\) (10\(^{20}\)/m\(^3\)) & 3.8 & 9.3 & 1.7 & 3.1 & 3.8 & 9.3 & 3.8 \\
\(\rho\) (10\(^{-5}\) \(\Omega m\)) & 3.5 & 1.8 & 13 & 5.2 & 3.5 & 1.8 & 3.5 \\
\(F^{2D}, F^{1D}\) & 2.4 & 2.4 & 1.8 & 2.6 & 0.76 & 0.72 & 0.80 \\
\hline
\end{tabular}
\caption{Length \(l\), width \(w\), thickness \(t\), and number of lines \(N\) parallel \(N\) of the samples. Some of the samples were annealed for the time \(a\) at 200 °C. Curie temperature \(T_C\), resistivity \(p\), and carrier concentration \(p\) were taken on reference samples from the corresponding wafers. The screening factor \(F^{2D}\) and \(F^{1D}\) were calculated using Eq. (1) and Eq. (2), respectively. Different samples from the same wafer are labeled a, b, or c.}
\end{table}
reflected in the temperature dependence of $\sigma_\parallel$ and the corresponding square resistance $\rho_{s}\parallel=\rho/s$ for zero magnetic field which are displayed in Fig. 1(b), respectively. This behavior is the focus of this Rapid Communication. The square conductivity change of sample 1$_{2D}$-a at different temperatures relative to $\sigma_\parallel$ measured at 20 mK is shown in Fig. 1(c) for zero magnetic field (filled squares) and $B=5$ T (open squares). For the temperature dependence of $\sigma_\parallel$ due to EEI, one obtains the following for a 2D system:\footnote{Equation 1}

$$\Delta \sigma_\parallel = \frac{F^{2D} e^2}{\pi \hbar} \log_{10} \frac{T}{T_0},$$

with a screening factor $F^{2D}$, the electron charge $e$, and the Planck constant $\hbar$. The square conductivity change observed experimentally follows such a logarithmical temperature dependency, independent of the applied magnetic field, as it is expected from the theory of electron-electron interaction. The slope in this $\log_{10}(T)$ plot is 0.77. This corresponds to a screening factor $F^{2D}$ of 2.4 [Eq. (1)], which is also close to the screening factor found in Co films [$F^{2D}$(Co) = 2.0...2.6].\footnote{Equation 1}

Does annealing of (Ga,Mn)As change the conductivity correction? Low temperature annealing of (Ga,Mn)As causes an out diffusion of Mn ions from interstitial sites of the lattice, where they act as double donors.\footnote{Equation 1} Hence low-temperature annealing increases carrier concentration, square conductivity, and Curie temperature.\footnote{Equation 1} The relevant parameters of the annealed sample 1$_{2D}$-a are listed in Table I (sample 1$_{2D}$-b). Both carrier concentration and square conductivity increased by a factor of $\sim$2 after annealing. The screening factor $F^{2D}$, describing the strength of EEI, however, remained unchanged, as is shown in Fig. 1(c). This demonstrates that the observed conductivity decrease is a universal phenomenon, as it is independent on the absolute value of $\sigma_\parallel$. A recent experiment of He \textit{et al.}\footnote{Equation 1} seems to be in contrast to our finding. These authors observed a reduction of the logarithmical slope of the resistivity due to low-temperature annealing. If we plot for our samples instead of $\sigma_\parallel$ the square resistivity change versus $\log_{10}(T)$ we obtain the same result. The change in square resistivity $\Delta \rho_{\parallel}$ is connected to the change in square conductivity $\Delta \sigma_\parallel$ by $\Delta \rho_{\parallel} = 1/\rho_{\parallel} - 1/\rho_{\parallel}^{2} = \rho_{\parallel}^{2} \Delta \sigma_\parallel$. Though $\Delta \sigma_\parallel$ remains unchanged by annealing, $\Delta \rho_{\parallel}$ does not. As $\rho_{\parallel}$ is decreasing due to annealing, also $\Delta \rho_{\parallel}$ is decreasing. From the data of He \textit{et al.}\footnote{Equation 1} we estimate an average screening factor $F^{2D}$ of 2.5. This is in good agreement with our results. A monotonic dependency of the logarithmical slope of the resistivity due to low-temperature annealing.

\textit{Conclusions.} For 2D samples (sample 1$_{2D}$-a, 1$_{2D}$-b, 2$_{2D}$, and 3$_{2D}$ in Table I). The discussion for the 2D samples will be in terms of the square conductivity $\sigma_\parallel=\sigma_{\parallel}$, as the conductivity corrections due to electron-electron interaction are expected to be independent on the absolute value of $\sigma_\parallel$. The conductivity $\sigma$ was obtained by inverting the resistivity $\rho=R/(ne)$, with the resistance $R$ of the investigated samples, $\sigma=1/\rho$. The square conductivity of sample 1$_{2D}$-a is displayed in Fig. 1(a) for temperatures between 20 and 600 mK in a perpendicular applied magnetic field $B$. The shape of $\sigma_\parallel(B)$ remains unchanged in this temperature range and is typical for ferromagnetic (Ga,Mn)As. The square conductivity maxima at $B=0$ stems from the anisotropic magnetoresistance\footnote{Equation 1} (AMR) and reflects the fact that $\sigma_\parallel$ for an in-plane magnetization is higher than for an out-of-plane magnetization. The positive slope of $\sigma_\parallel$ for $B>400$ mT, known as negative magnetoresistance (NMR), is discussed in terms of increased magnetic order,\footnote{Equation 1} or as a consequence of weak localization in three dimensions.\footnote{Equation 1} With decreasing temperature the square conductivity decreases without saturation. This behavior is also
The conductivity change of three 1D samples, taken relative to the conductivity at 50 mK and at zero magnetic field (filled symbols) and 3 T (open symbols), is shown in Fig. 2(c). The data points follow a $1/\sqrt{T}$ dependency independent of the applied magnetic field. Such a dependence is expected for EEI correction in 1D which is given by

$$\Delta \sigma = - \frac{F_{1D}^2 e^2}{\pi A h} \sqrt{\frac{\hbar D}{k_B T}}$$

with a screening factor $F_{1D}$, the wire cross section $A$, the diffusion constant $D$, and the Boltzmann constant $k_B$. Again, the conductivity decrease with decreasing $T$ can also be explained in terms of electron-electron interaction. The relevant screening factor $F_{1D}$ [Eq. (2)] ranges between 0.72 and 0.80. Also the value of $F_{1D}$ is close to the value found in Ni wires $[F_{1D}(\text{Ni}) = 0.83]^{22}$.

We expect a dimensional crossover from 1D to 2D or 3D at temperatures above 1 K where the thermal length $l_T$ becomes smaller than width and thickness of the wires. While data taken from sample 1D-b between 1.8 K and 8 K (not shown) are consistent with a 1D–2D transition, a $1/\sqrt{T}$ temperature dependence, expected for 1D systems, fits the data in this temperature regime equally well. A $\sqrt{T}$ temperature dependence, expected for a 3D system, however, is not consistent with the data.

Strong spin orbit scattering, as observed in (Ga,Mn)As, affects the screening factors $F^{2D}$ and $F^{1D}$ but not the corresponding temperature dependence. As we see no difference in the screening factor at $B=0$, where the dominating magnetic field is the spin-orbit field, and at $B=3$ T, where Zeeman splitting dominates, we conclude the effect of spin-orbit scattering on the screening factor is weak. This is consistent with previous work on Ni/(Ag,Au)/Ni films where only a weak dependence of the screening factor on spin-orbit scattering was found.

Our results obtained from 1D samples and 2D samples show that electron-electron interaction is dominating the conductance of (Ga,Mn)As in the low-temperature regime. Comparing our result with recent results of Honolka et al., the most obvious difference is the resistivity of the investigated samples. While the resistivity of the samples investigated in Ref. 14 is $\sim 7 \times 10^{-4} \, \Omega m$ at 300 mK, the resistivity of our samples is between 5.5 times (sample 2D) and 40 times lower (sample 1D-b). While the devices investigated by Honolka et al. are already close to a metal-insulator transition, where the conductance can be described by Altshuler-Aronov scaling, we are still on the metallic side of conductance where the conductance is dominated by electron-electron interaction. The good agreement of screening factors in 1D and 2D (Ga,Mn)As samples with those found in conventional metallic ferromagnets such as Co (Refs. 18 and 19) and Ni (Ref. 23) underlines that we are on the metallic side of conductance. The mechanisms causing the conductivity decrease in both ferromagnetic semiconductor (Ga,Mn)As and ferromagnetic metals seem to be very similar. A comparable result was found by Maliepaard et al. in n-doped GaAs.
While on the metallic side conductance was dominated by electron-electron interaction, close and beyond the metal insulator transition the conductance could be described by Altshuler-Aronov scaling.

In summary we have shown that the conductivity of (Ga,Mn)As decreases with decreasing temperature below 1 K. The observed conductivity decrease in wires and films on the metallic side of conductance can be described by EEI. The observed screening factors $F_{1D}$ and $F_{2D}$ are in good agreement with the screening factors found in conventional metallic ferromagnets.

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1 H. Ohno, Science 281, 951 (1998).
2 T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science 287, 1019 (2000).
3 M. Sawicki, J. Magn. Magn. Mater. 300, 1 (2006), and references therein.
4 D. V. Baxter, D. Ruzmetov, J. Scherschligt, Y. Sasaki, X. Liu, J. K. Furdyna, and C. H. Mielke, Phys. Rev. B 65, 212407 (2002).
5 P. Majumdar and P. B. Littlewood, Nature (London) 395, 479 (1998).
6 M. Sawicki, T. Dietl, J. Kossut, J. Igason, T. Wojtowicz, and W. Plesiewicz, Phys. Rev. Lett. 56, 508 (1986).
7 C. Timm, M. E. Raikh, and F. von Oppen, Phys. Rev. Lett. 94, 036602 (2005).
8 C. P. Moca, B. L. Sheu, N. Samarth, P. Schiffer, B. Janko, and G. Zarand, arXiv:0705.2016 (unpublished).
9 E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979).
10 G. Zarand, C. P. Moca, and B. Janko, Phys. Rev. Lett. 94, 247202 (2005).
11 H. T. He, C. L. Yang, W. K. Ge, J. N. Wang, X. Dai, and Y. Q. Wang, Appl. Phys. Lett. 87, 162506 (2005).
12 F. Matsukura, M. Sawicki, T. Dietl, D. Chiba, and H. Ohno, Physica E (Amsterdam) 21, 1032 (2004).
13 A. Van Esch, L. Van Bockstal, J. De Boeck, G. Verbanck, A. S. van Steenbergen, P. J. Wellmann, B. Grietens, R. Bogaerts, F. Herlach, and G. Borghs, Phys. Rev. B 56, 13103 (1997).
14 J. Honolka, S. Masmanidis, H. X. Tang, D. D. Awschalom, and M. L. Roukes, Phys. Rev. B 75, 245310 (2007).
15 P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. 57, 287 (1985).
16 M. Reinwald, U. Wurstbauer, M. Döppe, W. Kipferl, K. Wagenhuber, H.-P. Tranitz, D. Weiss, and W. Wegscheider, J. Cryst. Growth 278, 690 (2005).
17 E. L. Nagaev, Phys. Rev. B 58, 816 (1998).
18 M. Brands, A. Carl, O. Posth, and G. Dumpich, Phys. Rev. B 72, 085457 (2005).
19 M. Brands, C. Hassel, A. Carl, and G. Dumpich, Phys. Rev. B 74, 033406 (2006).
20 K. W. Edmonds, P. Boguslawski, K. Y. Wang, R. P. Campion, S. N. Novikov, N. R. S. Farley, B. L. Gallagher, C. T. Foxon, M. Sawicki, T. Dietl, M. Buongiorno Nardelli, and J. Bernholc, Phys. Rev. Lett. 92, 037201 (2004).
21 D. Neumaier, K. Wagner, S. Geißler, U. Wurstbauer, J. Sadowski, W. Wegscheider, and D. Weiss, Phys. Rev. Lett. 99, 116803 (2007).
22 T. Ono, Y. Ooka, H. Miyajima, K. Mibu, and T. Shinjo, J. Magn. Magn. Mater. 226, 1831 (2001).
23 B. L. Altshuler, A. G. Aronov, and A. Yu. Zuzin, Solid State Commun. 44, 137 (1982).
24 J. J. Lin, S. Y. Hsu, J. C. Lue, and P. J. Sheng, J. Phys. Chem. Solids 62, 1813 (2001).
25 M. C. Maliepaard, M. Pepper, R. Newbury, and G. Hill, Phys. Rev. Lett. 61, 369 (1988).