Magnetization-controlled spin transport in DyAs/GaAs layers

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Electrical transport properties of DyAs epitaxial layers grown on GaAs have been investigated at various temperatures and magnetic fields up to 12 T. The measured longitudinal resistances show two distinct peaks at fields around 0.2 and 2.5 T which are believed to be related to the strong spin-disorder scattering occurring at the phase transition boundaries induced by external magnetic field. An empirical magnetic phase diagram is deduced from the temperature dependent experiment, and the anisotropic transport properties are also presented for various magnetic field directions with respect to the current flow.

With the development of molecular beam epitaxy (MBE) techniques, rare-earth monoarsenides (RE-As) can now be grown on GaAs substrate with high quality [1,2]. Such magnetic semimetals host a number of interesting electronic and magnetic phases [3–7] mostly derived from the rare-earth elements. Integration of magnetic semimetal with semiconductor, e.g. GaAs, yields a new type of low-dimensional quantum structures where both charge and spin transport are of interest. The magnetotransport properties of these compounds, however, have been relatively unexplored with the exception of GaAs/ErAs/GaAs [8–10], for which the properties of carrier, magnetic phases, and electronic band structure have been studied in some detail. Here we report the results for magnetization-controlled spin transport in DyAs thin layers measured at low-temperatures and high magnetic fields.

Samples were grown by MBE on semi-insulating GaAs (001) substrates [11]. DyAs layer was grown at temperature ~ 500°C on top of the 200 nm undoped GaAs buffer layer, and then an undoped GaAs cap layer of about 20 nm was grown subsequently on top of DyAs. Three samples having DyAs layer thickness of 70, 270, and 600 nm have been characterized. The structural quality of the DyAs layers [11] is comparable with that of the GaAs/ErAs/GaAs grown by MBE [8]. For the electrical transport measurements we used a Hall bar geometry (width 500 µm) defined by standard optical lithography. Indium contacts were alloyed at ~ 400°C for electrical connections to both the electrons and holes in the DyAs.

The transport experiment was performed from room temperature down to 0.4 K in a 3He refrigerator, and with a magnetic field \( H \) up to 12 T; a standard low-frequency \( (<20\text{Hz}) \) lock-in technique was employed for measurements of the magnetotransport coefficients. To study the anisotropic properties, the magnetic field was oriented either perpendicular to the plane of DyAs, or in the plane and with a varying direction to the current flow \( J \).

Magnetoresistance characteristics are qualitatively similar for all three samples. In the following, we concentrate on the results from the sample with a DyAs layer thickness of 270 nm. In Fig. 1, we present the longitudinal magnetoresistances, \( R_{xx} \), measured at four typical magnetic field orientations at 0.4 K. Except for the case where magnetic field parallel to the current flow, positive background is seen in magnetoresistance. In each of the \( R_{xx} \) traces intrinsic signals from the magnetization manifest themselves as two distinct peaks, seen here at \( \sim 0.2T \) and \( \sim 2.5T \) respectively.

![Fig. 1. Magnetoresistances for the magnetic field perpendicular to the plane (line 1) and for three in-plane orientations with respect to the current flow (lines 2-4) at 0.4K. The magnetic field was swept from negative to positive direction (from the left to the right) with a varying direction to the current flow.](image-url)

We note that the \( R_{xx} \) trace, obtained here in a field sweep from negative to positive direction (from the left...
to the right in \( H \) axis), is strongly asymmetric about \( H = 0 \). We have reversed the field sweep direction and found that the curve is an exact mirror image of the previous trace. Such observations are unambiguous evidences for magnetization-controlled electronic transport in the DyAs layer.

Based on the discussion of the results in ErAs [4], we relate both of the peaks to the strong spin-disorder scattering occurring in magnetic phase transition regimes induced by external magnetic field. It should be mentioned that in GaAs/ErAs/GaAs only single magnetoresistivity peak has been observed at \( \sim 1T \) and ascribed to antiferromagnet to paramagnet transition [5]. We tentatively attribute the peak observed around 2.5T in DyAs to a transition of similar nature. The origin of the anomaly at about 0.2T in our DyAs samples is so far unresolved, but the resistance peak could be an indication of the transition between two different configurations in the antiferromagnetic phase. The possibility of multiple configurations in the antiferromagnetic phase is consistent with the results from temperature-dependent magnetization experiment, where two inflections showed up in the DyAs magnetization curves at temperatures around 6 and 8K, respectively [6]. Sharp peak and associated \( R_{xx} \) change influenced by weak magnetic field of 0.2T is, to some extent, similar to giant magnetoresistance observed in metal superlattices and granular materials [7].

In contrast with the largely isotropic magnetization properties of DyAs reported in [7], the electrical transport properties are essentially anisotropic: \( R_{xx} \) is very sensitive to the magnetic field-current flow configurations, i.e., the peak amplitudes and their positions (especially for the peak around 2.5T) vary with the field orientation. Furthermore, while it is absent in other field orientations, an additional peak in \( R_{xx} \) emerges at higher magnetic field of \( \sim 9.5T \) for the in-plane magnetic field oriented about 35° with respect to the current flow. Strongly anisotropic magnetoresistance in our experiments further indicates the effects of crystal field interactions at low temperature. Such strong effects were suggested by Child et al in their study on magnetic properties of a variety of RE-V compounds by neutron diffractions [8]. Like in other RE-V compounds [8], the magnetically aligned sheets in DyAs are expected to be perpendicular to (111) direction. Magnetotransport experiments on DyAs grown on (111) GaAs substrates, in addition to the present (001) data, are thus needed to clarify the issue.

The Hall resistance \( R_{xy} \) measured for the magnetic field perpendicular to the DyAs layer is extremely small, of the order of \( 10^{-3}\Omega \). Moreover, the overall shape of the Hall resistance is similar to that of \( R_{xx} \), which may be caused by mixing of transport coefficients. Extremely small Hall resistance is due to either high carrier concentration or electron-hole compensation. Lack of the information on carrier density and mobility prevents us from quantitative analysis of the experimental results. In particular, we were unable to assess the relative contribution from the electrons and that from the holes to the transport data, an issue demanding further studies.

![FIG. 2. Longitudinal resistivity against temperature before magnetization.](image)

As shown in Fig.2, the temperature dependence of the resistivity before magnetization \((H = 0)\) displays a dip around 8.5K followed by a sharp increase at lower temperature, with a tendency to saturate below 4.4K. At the transition point from antiferromagnetism to paramagnetism, a divergence of the resistivity’s temperature derivative is expected, as described in Reference [9]. The Neel temperature, \( T_N \), could then be inferred from the maximum of \( dR_{xx}(T)/dT \). The estimated value \( T_N \approx 8K \) is consistent with the magnetization measurements [5].

![FIG. 3. Longitudinal magnetoresistances for a magnetic field perpendicular to the plane at different temperatures. Inset: Magnetic field positions of valley (dots) and second peak (circles) in the longitudinal magnetoresistances at different temperatures, and the three magnetic phases (antiferromagnet I, II, and paramagnet) divided by them.](image)
The $R_{xx}$ traces have been recorded at different temperatures; several typical curves are shown in Fig. 3 for the $H$ field perpendicular to the plane and swept from negative to positive side. Again, the asymmetry of the $R_{xx}$ around $H = 0$, which shows a strong $T$ dependence and eventually disappears above $8 \text{K}$, reflects the intrinsic magnetization in the sample. It can also be seen from Fig. 3 that both of the peak positions shift towards lower magnetic field as the temperature increases. The amplitude of the first peak remains nearly unchanged up to $6.5 \text{K}$ while that of the second peak decreases monotonously within this temperature range. At temperatures above $6.5 \text{K}$, a drastic decrease of the first peak is detected; this peak disappears at $8 \text{K}$, which coincides with the Neel temperature $T_N \approx 8 \text{K}$. At the same time, the second peak shifts rapidly to the low-field side and then disappears at about $11 \text{K}$.

In order to summarize our observations, we assume that the valley between the two peaks represents the transition from one type of antiferromagnetism configuration (i.e., AFM I) to another (AFM II), and the second peak the transition point from the antiferromagnetism to paramagnetism (PM), to arrive at an empirical magnetic phase diagram, as sketched in the inset of Fig. 3. This phase diagram shows schematically the magnetic phase transition boundaries as critical magnetic field against temperature.

The temperature dependence of the magnetoresistance shows different behavior for the in-plane magnetic field. Here we consider the case for an in-plane magnetic field parallel to the current flow (not shown). The overall tendency of the first peak is nearly the same as that in Fig. 3; it also disappears around $8 \text{K}$. However, in contrast with the monotonous shift to the low-field side (as shown in Fig. 3), the second peak first shifts to higher field up to $8.5 \text{K}$, then moves down to the low-field side, and eventually approaches zero field at $16.5 \text{K}$, i.e., higher temperature is required to convert the antiferromagnetism to paramagnetism. The experimental results from a series of field-current configurations lead us to conclude that the AFM I configuration of the antiferromagnetism is weakly anisotropic and the AFM II is strongly anisotropic. Such anisotropy is believed to be caused by a combination of the strong crystal field and the strain/dislocations produced in the sample, since there is as large as two percent lattice mismatch between DyAs and GaAs. The details of the magnetization-controlled anisotropic transport will be published elsewhere.

In summary, we have studied the magnetotransport properties of the epitaxial DyAs layers grown on GaAs. It is shown from the longitudinal magnetoresistance data that the electronic transport is controlled by the magnetization. The Neel temperature $T_N$, deduced from temperature dependence of $R_{xx}$ is about $8 \text{K}$, and is consistent with the magnetization results [7]. We have observed two distinct peaks in the magnetoresistances which are attributed to strong spin-disorder scattering at the magnetic phase boundaries. Our data suggest that there exist more than one type of antiferromagnetism configurations in DyAs grown on (001) GaAs, which is qualitatively different from ErAs where only one peak has been observed. Strongly anisotropic transport properties further support the notion that crystal field interaction plays an important role in the magnetism of epitaxial DyAs layer on GaAs.

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