Geometrically enhanced extraordinary magnetoresistance in semiconductor-metal hybrids

This item was submitted to Loughborough University's Institutional Repository by the/an author.


Metadata Record: https://dspace.lboro.ac.uk/2134/12781

Version: Published

Publisher: © The American Physical Society

Please cite the published version.
Since extraordinary magnetoresistance (EMR) was discovered in 2000, improvements to magnetic field sensors have been considered. This has been of particular interest in the area of ultrahigh-density magnetic recording. Future read heads based on the EMR effect have many potential advantages over existing devices based on giant magnetoresistance (GMR). The EMR effect is particularly exciting with regards to its practical applications as significant values of magnetoresistance at room temperature and in low magnetic fields can be obtained. Where observed, these systems contain exclusively nonmagnetic materials in their construction therefore achieving a high signal-to-noise ratio. Here, we present findings that have the potential to extend the EMR effect to a wider range of semiconductor materials via a huge geometrical enhancement. We also look at the link between the EMR effect and the large, linear, and unsaturating magnetoresistance discovered in the silver chalcogenides with the use of a random branch and droplet model (RBDM).

EMR was initially discovered in modified van der Pauw disks consisting of a mobility narrow gap semiconductor outer disk (InSb of radius $r_b$ with $\sigma_0 = 1.86 \times 10^4 \ \Omega^{-1} m^{-1}$ and $\mu = 45 \ 500 \ cm^2/V \ s$) with an embedded metallic inclusion (Au of radius $r_a$ with $\sigma_0 = 4.52 \times 10^7 \ \Omega^{-1} m^{-1}$ and $\mu = 50 \ cm^2/V \ s$). The filling factor, $\alpha$, can be defined as $\alpha = r_a/r_b$. Magnetoresistance values of over one million percent were reported at room temperature in an applied magnetic field of 5 T for a system with $\alpha = 13/16$. The extremely large magnetoresistance values arise from the redistribution of current paths throughout the system as a perpendicular magnetic field is applied. This current redistribution appears from the Lorentz force acting on the charge carriers, creating a Hall angle that approaches 90° in large magnetic fields. This leads to two regimes: one of low resistance at low fields (short circuit), here the majority of the current flows through the metallic region; the other of high resistance at high fields (open circuit), here the current is expelled from the metallic region and is forced to flow around the outer semiconductor material of much higher resistance. Since its discovery, EMR has been shown to arise in various experimental systems, including linear devices produced via conformal mapping.

Using the finite-element method via COMSOL MULTIPHYSICS (Ref. 8) the EMR effect found by Solin et al. has been modeled and the mechanism verified. In order to replicate the experimental system as precisely as possible we created a two-dimensional (2D) model with the transverse magnetic field included by the 2D magnetococonductivity tensor,

$$\sigma_{ij} = \frac{\sigma_0}{1 + (\mu H)^2} \left( 1 - \mu H \right)$$

Four point contacts were included around the disk perimeter; two contacts inject the current into the system while the other two were used to measure the change in electrical potential. This allowed the magnetoresistance to be calculated using the standard definition,

$$\Delta R/R_0 = \frac{R(H) - R(0)}{R(0)}.$$
The EMR effect is strongly dependent on the geometry of the system; unlike many other magnetoresistance effects the geometrical component of the magnetoresistance is larger than the physical one. This geometrical contribution depends not only on the shapes of the conducting and semiconducting materials but also on the positions of the contacts in the system. As a result, our model was adapted in order to investigate the effect of the system geometry on the magnetoresistance. To enhance the magnetoresistance the difference between the low and high resistance regimes is required to be a maximum. The geometry in which the largest magnetoresistance value was obtained contained a multibranched metallic inclusion; see Fig. 2(b). This geometry shows a four order of magnitude increase in magnetoresistance over the experimental geometry containing a circular metallic droplet of the same filling factor (see Fig. 2). Many geometries were investigated with such multibranched geometry (as in Fig. 2(b)) showing the largest enhancement. We do not believe this geometry to be the most optimal configuration and other multibranched geometries may show further enhancement. However, the significant result is in showing that such huge enhancements can be achieved by modification of the system geometry.

When this multibranched geometry (with $\alpha=0.5$) is compared to geometries containing circular metallic regions of larger filling factors (for example, $\alpha=15/16$) the enhancement is less dramatic, being only approximately two orders of magnitude. This comparison is useful as the low- and high-field regimes have a similar composition for such filling factors. The idealized current path in zero field is a straight line from the contacts to the nearest point in the metallic region, creating the lowest resistance path. However, the idealized high magnetic field regime is one where the current flow is directed around the disk periphery of much more resistive semiconducting material.

In order to understand this geometrical enhancement we look to the current distribution in the system, see Figs. 3(c) and 3(d). Here, we see that the current distribution is more diverse and complex than the one we found for systems containing circular metallic droplets as in experiments by Solin et al. [Figs. 3(a) and 3(b)] but in general the same mechanism can be observed. From the current streamlines we see that in all cases the current flow is highly inhomogeneous and changes significantly with magnetic field. Without magnetic field the current direction is always perpendicular to the metallic surface and the majority of the current flows through the metal. The new system geometry means that the low resistance path has an extremely low resistance. The majority of the current flows through the lower horizontal bar [as indicated in Fig. 3(c) where the large horizontal black arrows indicate the largest current flow] with only an extremely small fraction of the current path passing through semiconducting material. The high-field limit [see Fig. 3(d)] also enhances the magnetoresistance due to the geometry. The application of a magnetic field forces an increasing proportion of the current to flow through the semiconductor. In large fields the current is tangential to the metallic surface with the current thus avoiding the metal. The path the current takes in the semiconductor is lengthy and becomes extremely...
large magnetoresistance values are to be produced the appearance of a Schottky barrier should be considered in design. The semiconductor-metal interface is required to be Ohmic in behavior; the formation of a Schottky barrier would decrease the resulting EMR effect. Finite-element modeling has been used previously to investigate the EMR effect. However, investigating the effect of the system geometry in this way is unique.

The silver chalcogenides, for example, Ag$_2$Se and Ag$_2$S$_2$Te, are another example of a large magnetoresistance effect arising in semiconductor-metal hybrid systems. With $\delta=0$, the materials are semiconducting. However, a small excess ($\delta$) of silver added to the materials caused a large, linear, and unsaturating magnetoresistance. The microstructure of these materials has been documented where the excess silver forms a branched silver network (forming along grain boundaries) with silver droplets interdispersed in the semiconducting material. This two-phase nature is analogous to the EMR effect and based on these findings we have created a RBDM. This model was created in order to mimic the microstructure of the silver chalcogenides with randomly sized, positioned, and orientated branches and droplets. This model contains an equal filling factor for both branches and droplets with the total filling factor, $\alpha=0.29$. The material parameters used in this model are now given: semiconducting Ag$_2$Se has $\sigma_0=5 \times 10^4$ $1/\Omega$ m with $\mu=2500$ cm$^2$/V s while the excess silver has $\sigma_0=6.62 \times 10^7$ $1/\Omega$ m with $\mu=70$ cm$^2$/V s.

Figure 4 shows the magnetoresistance as a function of magnetic field ($H$ up to 5.5 T as in experiment) for a RBDM geometry. Here, we see a quasilinear dependence on magnetic field as observed experimentally in the silver chalcogenides. Here $\alpha=0.29$ with the disk radius being 0.5 $\mu$m, with purely diffusive transport considered.
slinear dependence on magnetic field. The silver chalcogenides contain a much larger and more complex formation of conducting structures without an equal area of metal forming branches and droplets. We believe that averaging many possible configurations would produce a more linear response. The magnitude of the effect is significantly smaller than that found in the modified van der Pauw disk geometry [Fig. 2(a)]. This is due to the low mobility of the semiconductors in these materials and the fact that the conducting regions occur in small disjointed fragments. The magnitude of the magnetoresistance given in Fig. 4 is in very good agreement with the experimental data (at room temperature). This RBDM geometry appears to have similarities to other theoretical models\(^\text{16}\) including a random resistor network that has also shown to exhibit a linear magnetoresistance.\(^\text{17}\)

Here, we have formed a model able to reproduce experimental EMR results with good agreement. This model has enabled the mechanism behind the effect to be further investigated and established with the use of current flow diagrams. This model was then developed to investigate the effect of the system geometry on the magnetoresistance. The magnetoresistance was found to be enhanced by over four orders of magnitude for a geometry containing a multibranched metallic region. This enhancement could be practically significant as it may allow for other semiconducting materials, with less ideal material parameters, for example, silicon, to be used in EMR devices. Finally, a RBDM geometry was utilized in an attempt to replicate the large, linear and unsaturating magnetoresistance found in the silver chalcogenides. Our model shows a quasilinear response of the same magnitude as in experiments.

---

\(^{8}\)t.h.hewett@lboro.ac.uk