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Extraordinary Magnetoresistance of an Off-Center van der Pauw Disk

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1. Introduction

We have recently shown that non-magnetic inhomogeneous narrow-gap semiconductor van der Pauw (vdP) disks with concentric metallic inclusions embedded inside the semiconductor material and a 4-fold symmetric set of electrical contacts on the disk periphery such as that shown schematically in the left panel of Fig. 1 can have a greatly enhanced room temperature magnetoresistance (MR), which we called extraordinary MR or EMR. [1,2] The EMR of such a composite structure not only can be much larger than the MR of a homogeneous disk made of the same semiconductor material, but also far exceeds the MR of magnetic materials exhibiting giant MR (GMR [3]) or colossal MR (CMR [4]). Devices employing the EMR effect are thus of potential technological importance for use as magnetic sensors in a number of applications.

One of the most intriguing applications for EMR is read heads for high density magnetic recording. This application will require devices of mesoscopic size. Fabrication of mesoscopic vdP disks with a concentric internal metallic inclusion or shunt will be extremely difficult. In contrast fabrication of mesoscopic rectangular plates with external shunts should be much easier. Using bi-linear conformal mapping [5] we have demonstrated [2] that such plates are electrically equivalent to the internally shunted vdP structure if the internal circular shunt is displaced to an off-center position as shown in the right panel of Fig 1. Moreover, the off-center disk (and corresponding plate) is expected to produce a higher EMR than the centered disk.

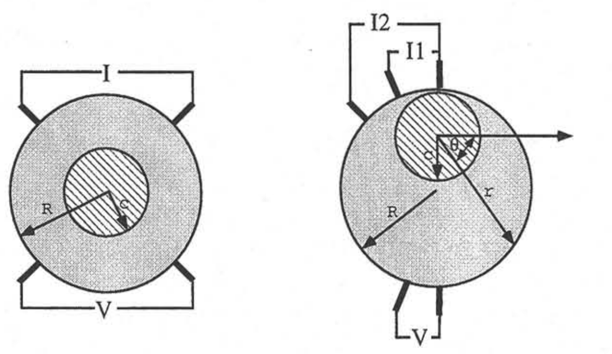

Fig. 1. Left panel – A centered symmetric van-der Pauw disc (shaded region) with a concentric embedded cylindrical metallic inhomogeneity (hatched region) and 4- symmetric leads. Right panel – An off-centered van der Pauw disk (shaded region) with an embedded cylindrical metallic inhomogeneity (hatched region) and asymmetric leads. I, I1 and I2 are current leads. V indicates voltage leads.

This EMR can be further increased by employing an asymmetric electrode configuration (see right panel of Fig. 1) which has the added advantage of providing self-biasing, [6]e.g. an asymmetric response to + and – applied magnetic field. Accordingly, we report here measurements of the EMR of such an off-center vdP disk with two distinct asymmetric lead configurations. We also calculate the EMR of the off-center disk by solving the appropriate Laplace boundary value problem using no adjustable parameters and find that our calculations are in good agreement with experiment.

2. Experimental Details

The off-center vdP disks were prepared from metal organic vapor phase epitaxy grown epilayers of Te-doped n-type InSb. A buffer layer of 200 nm undoped InSb was grown on a 4" semi-insulating GaAs substrate (resistivity > 1 x 10^{17} Ω•cm). A 1.3 μm active layer of InSb (concentration n = 2.11×10^{16} cm^{-3} and mobility μ = 40,200 cm^2/Vs) was deposited on the buffer layer and capped by a 50 nm InSb contacting layer (n ~ $1.5 \times 10^{17} cm^{-3}$). This epitaxial sequence was passivated by a 200 nm layer of Si_3N_4. The wafers were photolithographically patterned into chips bearing mesas for the off-center vdP disks. The internal circular shunt embedded in the disk, together with the mesa contact pads were simultaneously metallized with a Ti/Pt/Au stack, with Au the dominant component. Additional details of the sample preparation and measurement are given elsewhere. [1]

3. The Off-Center disk Boundary value problem

As illustrated in the right panel of Fig. 1, the radii of the semiconductor and the metallic inhomogeneity are R and c, respectively. A polar coordinate system with its center at the center of the metallic inhomogeneity is used, so that every point at the periphery of the semiconductor disk has coordinates r and θ as indicated. We define the angle coordinates of the two edges of one current electrode as ϕ_1 and ϕ_2 (not shown in Fig. 4), and for the other current electrode as ϕ_3 and ϕ_4, with $\phi = \phi_1 - \phi_2 = \phi_3 - \phi_4$ as the angular width of the current electrodes. We also assume that the uniform thickness of the device is t, and $\beta=\mu H$, $\beta_o=\mu_o H$, $\omega=\sigma/(1+\beta^2)$, $\omega_o=\sigma_o/(1+\beta_o^2)$ where $\sigma(\sigma_o)$ and $\mu(\mu_o)$ are the permittivity and conductivity, respectively of the semiconductor (metal). We solve this boundary value problem analytically, and obtain the electrical potential U on the periphery of the device as a function of magnetic field H, the radii of the semiconductor vdP disk and metallic inhomogeneity, as well as the position on the semiconductor periphery designated by r and θ. Taking note that $\sigma_0 >> \sigma$ and $\mu_0 << \mu$, we find that to a good approximation

$$U(H,r,\theta)=\frac{(1+\beta^2)Ir}{\sigma\pi t\varphi R}\sum_{n=1}^{\infty}\frac{1-\tau^{2n}}{n^2\left(J^2+K^2\right)}\times \quad (1)$$

$$[(JS-KT)\cos n\theta+(KS+JT)\sin n\theta]$$

where $J = 1 + \tau^{2n}$, $K = \beta(1-\tau^{2n})$ and $\tau = c/r$ while

$$S = \sin n\phi_2 - \sin n\phi_1 - \sin n\phi_4 + \sin n\phi_3 \quad (2)$$

and

$$T = \cos n\phi_1 - \cos n\phi_2 - \cos n\phi_3 + \cos n\phi_4 \quad (3)$$

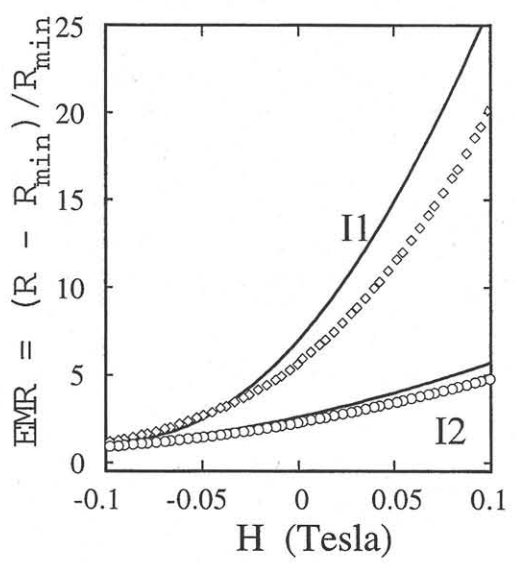

Fig. 2 The field-dependence of the magnetoresistance of the off-centered InSb vdP disks with two different current electrode settings. The solid lines and symbols represent calculated and measured results, respectively.

4. Comparison with Experiment

Given the solution for the potential from Eqs. (1) – (3) and using a constant current input, we can deduce the resistance for any electrode configuration and from this the EMR where

$$\mathrm{EMR}(H) = [R(H) - R_{min}]/R_{min}, \quad (4)$$

$R(H) = \Delta U(H,r,\theta)/I$ and R_{min} is the minimum resistance which for a symmetric lead configuration occurs at H = 0 but for an asymmetric lead structure, occurs at finite positive or negative field.

For the device studied here, the two current electrodes of I1 are centered at $\theta = \pi/2$ and $\theta = 0.712\pi$, those of I2 are centered at $\theta = \pi/2$ and $\theta = 0.884\pi$, respectively. The voltage electrodes are centered at $\theta = 1.413\ \pi$ and $\theta = 3\pi/2$, respectively. The electrodes all have a angular width ϕ of 8^0, and c/R = 9/16.

Figure 2 shows the calculated EMR for this device compared with the experimental results for both the I1 and I2 settings with an applied magnetic field of up to 1000 Gauss. In the calculation we have set the mobility of the semiconductor as 40,200 cm^2/Vs, the same as in the experiments. Note that the calculation has no adjustable parameters. The discrepancy between the measured and calculated EMR in Fig. 2 is most likely due to the embedded metal-semiconductor interface contact resistance which has not been accounted for in our calculation.

When compared with the EMR of a centered vdP disk with a concentric internal shunt, [1] the results in Fig. 2 have two prominent differences. First, the EMR in Fig. 2 is asymmetrical with respect to the direction of the magnetic field so the effective resistance of such devices reaches a minimum at finite magnetic field instead of at zero field. This kind of self-bias EMR response can be very useful for magnetic sensor applications since it allows direct measurement of + (up) and – (down) fields without the need for an external bias element. [6] Furthermore, note that the unit of the ordinate scale in Fig. 2 is absolute value instead of percent. Thus for the I1 lead structure, the EMR is of order 1500%. This is more than an order of magnitude larger than the EMR of a centered vdP disk of the same materials with the same size inhomogeneity.

5. Conclusions

Off-center vdP disks of InSb with a cylindrical Au inhomogeneity exhibit a much higher EMR than comparable centered vdP disks. The EMR depends strongly on the position of the electrical contacts. Analogous comformally mapped off-center vdP rectangular plates which are much more amenable to mesoscopic fabrication should exhibit comparable EMR. The enhanced EMR of off-center vdP disks can be computed with reasonable accuracy using analytic solutions to the Laplace boundary value problem.

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