Tuning the inherent magnetoresistance of InSb thin films

Tong Zhang,[a)] J. J. Harris, W. R. Branford, Y. V. Bugoslavsky, S. K. Clowes, and L. F. Cohen[b)]
Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BZ, United Kingdom

A. Husmann
Cambridge Research Laboratory, Toshiba Research Europe Limited, 260 Cambridge Science Park, Cambridge, United Kingdom

S. A. Solin
Department of Physics and Center for Materials Innovation, Washington University in St. Louis, 1 Brookings Drive, St. Louis, Missouri 63141

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We have investigated the 300 K inherent magnetoresistance of undoped InSb epilayers grown on GaAs(001) by molecular-beam epitaxy. The magnetoresistance of these films can be described well using a simplified model that incorporates gradation of properties away from the InSb/GaAs interface and the interplay between conduction and impurity bands. Although there is no significant intrinsic contribution in InSb bulk crystalline (001) materials due to its isotropic Fermi surface and mobility tensor, the linear and quadratic terms in the magnetoresistance as well as the overall magnitude can be tuned by varying the film thickness from 100 to 2000 nm. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2162666]

Magnetoresistance (MR) sensors are employed in many different areas, from position sensing in automotive applications to magnetic bit sensing in computer hard disks.[1] It has been well established since the 1960s that, in addition to using Corbino geometry, MR can be enhanced by various extrinsic processes such as in-plane conductivity inhomogeneity, in-plane geometric pathway inhomogeneity, and the geometry of the electrode placement.[2,3] For example, the extraordinary magnetoresistance effect produces a huge boost to the low-field MR in InSb,[4] for possible ultrahigh-density recording media (>1 T bit/in^2) in nanoscale devices.[5]

Recently, it has been shown that a material with a high mobility and a small but linear MR patterned into the Corbino geometry[6] will yield a high-field unsaturating MR behavior. It is interesting that materials which offer such inherent MR properties are often little understood. A model based on compositionally inhomogeneous material with mobility inhomogeneity in the plane has been proposed[7] to explain the unsaturating linear MR. In this letter, we demonstrate that another form of inhomogeneity–mobility inhomogeneity perpendicular to the plane (MIPP), explored previously in the context of the galvanomagnetic properties of samples with surface layers[8,9] or heterojunctions,[10–13] produces large MR even in thin films and is inherent to InSb film growth. We show that the overall magnitude and linearity of the MR can be tuned over a large range by varying the film thickness, in the present study from 100 to 2000 nm. We also introduce an approximate model, based on appropriate simplifications, that describes the salient features and reinforces our understanding of the films.

InSb films were grown by molecular-beam epitaxy on semi-insulating GaAs(001) substrates in a VG Semicon V80 system with a base pressure of 10^{-10} mbar. An undoped InSb buffer layer was deposited at “low temperature” (LT), i.e., 300 °C, prior to the growth of undoped InSb active layers. The growth details can be found elsewhere.[14,15] MR measurements were performed in a perpendicular magnetic field of up to 8 T in clover-leaf van der Pauw (vdP) geometry. Figure 1 presents the MR versus normalized field, μB, with insets showing the sample geometry and the MR as a function of non-normalized magnetic field. Also presented are the transport properties of an n-type InSb bulk sample, showing negligible MR. There is no sign of saturation of the MR for any film up to our maximum field of 8 T. The apparent mobility (μ) and carrier density (n), calculated using a single-layer single-carrier model using low-field Hall measurements are shown in Table I.

We approximate the MR functional form as a power series in μB

$$\mathrm{MR} = \Delta\rho(B)/\rho_0 = \alpha \cdot |\mu B| + \beta \cdot (\mu B)^2. \quad (1)$$

The inset to Fig. 2 shows $d(\mathrm{MR})/d(\mu B)$ vs μB, in which two regimes of behavior are evident for all the films: a low-field

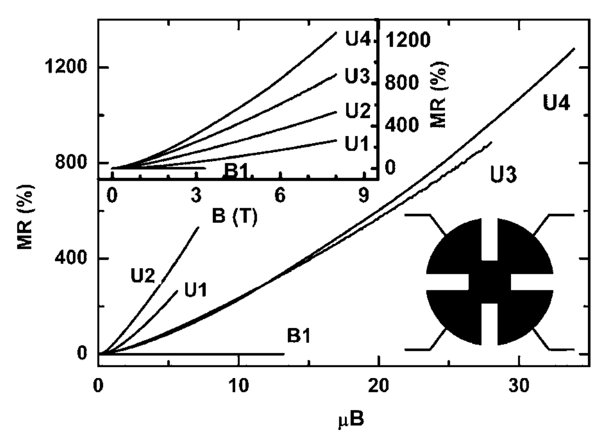

FIG. 1. MR of the InSb films in clover-leaf vdP geometry (schematically drawn in the lower inset), as a function of perpendicular magnetic field up to 8 T (upper inset) and μB (the main body).

[a)]Electronic mail: tong.zhang@imperial.ac.uk
[b)]Author to whom correspondence should be addressed; electronic mail: l.cohen@imperial.ac.uk

TABLE I. The "apparent" electrical properties of undoped InSb films grown on GaAs(001) substrates with the thickness between 100 and 2000 nm and an InSb bulk sample.

Samples	Undoped InSb					InSb bulk
	LT buffer	U1	U2	U3	U4	B1
Thickness (nm)	20	100	300	1000	2000	5×10^5
μ(m^2/V s)	0.035	0.79	1.3	3.5	4.3	4.0
n($\times10^{16}$ cm^{-3})	49	4.8	3.9	1.8	1.9	120

regime where the linear term $\alpha=0$, i.e., the films show purely quadratic behavior, and a high-field regime where α is finite. The main graph in Fig. 2 shows the values of α, quadratic term (β) and the linearity ratio α/β taken from the high-field regime. Both α and β increase for thinner films while the linearity ratio peaks at 1 μm.

Although bulk InSb has an isotropic Fermi surface and mobility tensor and therefore lacks intrinsic MR, our results can be understood qualitatively once it is appreciated that inherent MIPP occurs in the films. Quasi-linear MR behavior arises from magnetic-field-induced changes to the current distribution, with the major fraction being forced to flow in progressively lower mobility regions (nearer the interface) as the magnetic field is raised. In order to create MR of significant magnitude, which is also unsaturating and has a linear component, the film needs to have a wide range of mobility present. This would explain the maximization of the MR at a thickness where the surface layers have reached high, bulk-like mobility but the degraded layers underneath still play a significant role in conduction. A full theoretical description of the MR behavior of these InSb films is extremely complex and beyond the scope of this letter; however, most of the salient experimental results can be explained using a simplified model with the following features:

(a) Current can flow in the conduction band (CB) and an impurity band (IB) formed by the overlapping wave functions of defect donors associated with the dislocations[16] (hence also depth dependent)—as well as contributing another low-mobility conducting channel, this may have a nonstandard magnetoconductivity tensor;[17,18]

(b) The model takes into account the depth variation of the CB and IB properties, but neglects the possibility of the magnetic field affecting such parameters as the IB mobility (by inducing changes in the impurity wave functions) or CB mobility (from the cyclotron motion of the electrons);

(c) Although the variation in Hall coefficient with depth generates circulating currents in the transverse and growth directions, producing an interdependence of the magnetoconductance components, we have simplified this by setting boundary conditions appropriate to small metal contacts on the periphery of a clover-leaf vdP sample, and assuming, as all previous contributors[8–13] have done, that the current in the growth direction flows only through these contacts. Unlike the isolated layer model,[11–13] we also assume the same lateral electric field distribution at all depths, since we expect (i) the graded nature of the samples, (ii) the overlap of potential distributions from adjacent planes, and (iii) any current in the growth direction acting to minimize the field differences. This is equivalent to the formalism of Kane *et al.*,[10] which is experimentally more appropriate than the isolated-layer model for dissimilar layers in close proximity;[11]

(d) The depth-dependent properties have been derived from a differential Hall analysis of the samples, which replaces the continuous distribution of parameters by a step-like one, for both types of conducting channels.

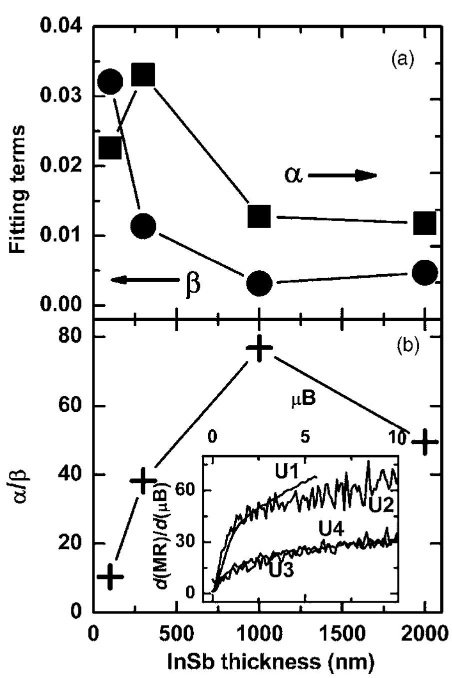

FIG. 2. Fitting parameters α (linear): ■ and β (quadratic): ● and the linearity ratio α/β: + for MR vs μB at high field as a function of film thickness. The inset is the first derivative of MR as a function of magnetic field.

In order to extract the properties for each step, we assume that for a series of N samples of various total thicknesses t_i, ($i=1$ to N, with all $t_i>t_{i-1}$), each sample of thickness t_i can be considered as consisting of a top layer of thickness (t_i-t_{i-1}), and an underlying layer with the same properties as the sample of thickness t_{i-1}. As a result, the low-field data μ and n presented in Table I can be used to calculate μ_i and n_i for each differential step (t_i-t_{i-1}).[14] In order to determine the IB contribution, we apply the two-channel model to each differential step of the sample, writing the relationship as

$$\mu_{i:\mathrm{CB}} = \mu_i \frac{1+r_n r_\mu}{1+r_n r_\mu^2}, \quad n_{i:\mathrm{CB}} = n_i \frac{1+r_n r_\mu^2}{(1+r_n r_\mu)^2}, \qquad (2)$$

where r_n and r_μ denote the ratios of carrier density and mobility of the IB to those of the CB, respectively. We consider

TABLE II. The electrical properties deduced from the differential model (subscript: diff) and the fitted values of the IB and CB properties for the layers defined by the differential model.

Layers	No. 1 20 nm	No. 2 70 nm	No. 3 220 nm	No. 4 670 nm	No. 5 1520 nm
μ_{diff}(m^2/V s)	0.035	0.85	1.5	4.2	4.8
n_{diff}($\times 10^{16}$ cm^{-3})	49	4.9	3.9	1.6	2.1
μ_{IB}(m^2/V s)	0.000 54	0.0091	0.014	0.028	0.029
n_{IB}($\times 10^{16}$ cm^{-3})	516	28	19	5.4	5.1
μ_{CB}(m^2/V s)	0.042	0.91	1.6	4.3	4.9
n_{CB}($\times 10^{16}$ cm^{-3})	34	4.4	3.5	1.6	2.0

each film as being composed of the appropriate "s" steps with thicknesses of $d_i(i=1$ to $s)$, and then sum the magnetoconductance tensors for the CB and IB in all of the s steps to give longitudinal and transverse components as

$$\sigma_{xx}^{s}(B) = \sum_{i=1}^{s} n_{i:\mathrm{CB}} d_i e \mu_{i:\mathrm{CB}} \left[\frac{1}{1+\mu_{i:\mathrm{CB}}^2 B^2} + \frac{r_n r_\mu}{1 + r_\mu^2 \mu_{i:\mathrm{CB}}^2 B^2} \right],$$

$$\sigma_{xy}^{s}(B) = \sum_{i=1}^{s} n_{i:\mathrm{CB}} d_i e \mu_{i:\mathrm{CB}}^2 B \left[\frac{1}{1+\mu_{i:\mathrm{CB}}^2 B^2} + \frac{r_n r_\mu^2}{1 + r_\mu^2 \mu_{i:\mathrm{CB}}^2 B^2} \right]. \quad (3)$$

Standard matrix inversion is then used to give the longitudinal resistivity, ρ_{xx}, for MR calculation.

Table II lists the layer parameters extracted from fitting the experimental data as shown in Fig. 3. As expected, the fitted electrical properties of the IB and CB differ from those extracted at low field;[16] in particular, the IB mobilities are significantly lower than low-field values. Also note that the parameters shown in Table II do not describe the high-field Hall data particularly well. Nevertheless, we stress that a simple two-layer model, for example,[19] yields a saturating quadratic MR behavior which would not explain our observations, while the model proposed here certainly captures most of the salient features of the MR. The linearity results in Fig. 2 show that the optimal thickness, where the linearity ratio is at its maximum, is close to 1 μm, above which the top layers are approaching bulk mobility values.[17,20] The model we put forward can certainly account for this result.

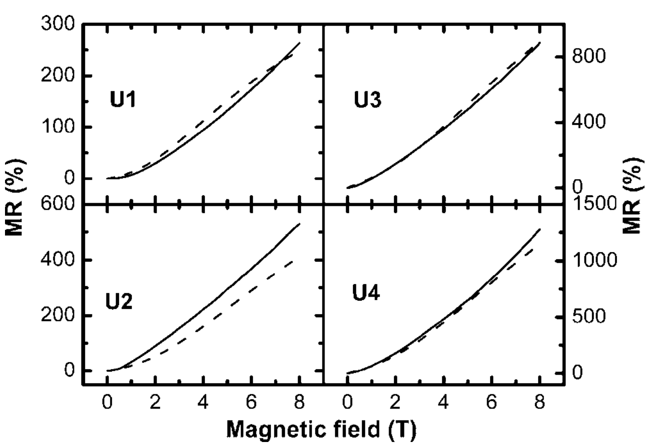

FIG. 3. The fitting of the MR of the InSb films. The fitting method employed here is a combination of a differential model and a shared contribution of impurity and conduction bands.

To summarize, we have demonstrated that the inherent MR properties of thin InSb films are tunable over a wide range by virtue of the mobility inhomogeneity in the growth direction away from mismatched GaAs(001) substrates. Moreover, the simplified model we have set out provides a useful basis for understanding how to tailor the MR characteristics for particular applications without unduly compromising the mobility.

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