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Magneto-transport and magneto-optics in composite media with a two-dimensional microstructure

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Abstract

In the presence of a strong, in-plane magnetic field $\boldsymbol{B}$, the electrical transport and optical properties of thin composite films with a columnar microstructure exhibit surprising new forms of behavior. These are caused by the appearance of local currents which flow up and down in the perpendicular direction, and increase as $|\boldsymbol{B}|$ without any saturation. In a conducting composite, this results in a positive, non-saturating magneto-resistance, that is proportional to $\boldsymbol{B}^2$. When the microstructure is periodic, the magneto-resistance exhibits a strong dependence on the precise directions of $\boldsymbol{B}$ and of the average in-plane current $\langle \boldsymbol{J} \rangle$ with respect to that microstructure. The optical properties of metal/dielectric composite films with a periodic columnar microstructure can also exhibit such strong directional variability, if the microstructure and $\boldsymbol{B}$ and the frequency are adjusted so that the system is in the vicinity of a sharp quasi-static resonance. In a metallic film with a periodic array of small, sub-wavelength holes, it is possible to achieve a strong, anisotropic transmissivity by adjusting the system parameters so as to operate near a $\boldsymbol{B}$-dependent "surface plasmon resonance".

Keywords: Magneto-transport; Magneto-optics; Composite media; Columnar microstructure; Microstructured films

When a strong magnetic field is applied to a macroscopically heterogeneous or composite medium, where at least one constituent is an electronic conductor, the local Hall effect can lead to spectacular behavior, both in electrical transport and in optical response. These phenomena are most striking in the case of a periodic columnar microstructure, i.e., when there exists a columnar axis along which everything is uniform, while in the perpendicular plane the microstructure is periodic. Such microstructures can be fabricated using modern methods for growth and microstructuring of thin films. Thus, it is possible to produce a highly doped semiconducting film, with a large Hall mobility μ, and then etch in it a two-dimensional collection of perpendicular cylindrical holes. When a strong magnetic field $\boldsymbol{B}$ is applied in the plane of such a film, and a current is sent through it, local currents appear which flow also along the columnar axis. Moreover, whereas the planar current components always saturate for a finite density of holes when $|\mu\boldsymbol{B}| \gg 1$, the columnar current components usually increase as $|\mu\boldsymbol{B}|$ without any saturation. Thus, even though the average current component in that direction vanishes, the local currents along that axis, which must of course flow in both directions, are exceedingly important: They lead to a non-saturating magneto-resistance that increases as $(\mu\boldsymbol{B})^2$. This has recently been shown explicitly, for random arrays of insulating inclusions, by using a self consistent effective medium approximation, which takes into account some exact relations that must hold in the case of columnar microstructures [1]. Earlier theoretical and calculational work on periodic arrays of insulating inclusions showed a non-saturating magneto-resistance, but it also showed a great sensitivity to the precise directions of the magnetic field $\boldsymbol{B}$ and the volume averaged current density $\langle \boldsymbol{J} \rangle$ when those are in the film plane [2]. Those results were verified in an experiment on magneto-transport in a thin film of n-doped GaAs, a free-electron conductor, which had a square array of holes etched in it (see Fig. 1) [3]. Similar microstructures, based upon

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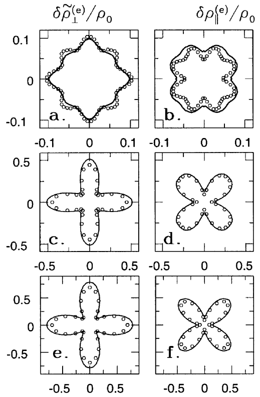

Fig. 1. Polar plots of $\delta\rho_{\parallel}^{(e)}(\boldsymbol{B})/\rho_0$ and $\delta\tilde{\rho}_{\perp}^{(e)}(\boldsymbol{B})/\rho_0$ for three samples of 300 nm thick GaAs films with a square array of etched holes, approximately shaped as circular cylinders perpendicular to the film plane, at the highest magnetic field available $|\boldsymbol{B}| = 12$ T, i.e., $\mu|\boldsymbol{B}| = 3$. Experimental points are shown as open circles, theoretical fits as full lines. From top to bottom the geometrical hole radii are (a), (b) 55 nm, (c), (d) 110 nm, and (e), (f) 130 nm. The fitted cylinder radii (fitted in order to take into account the changes in bulk semiconductor properties near surfaces and interfaces) used in the calculations, were 73, 180, and 215 nm, respectively, and a normalized effective film thickness of $l/a = 0.45$ was also used instead of the lithographic value $l/a = (300\,\text{nm})/(500\,\text{nm}) = 0.6$ (after Ref. [3]).

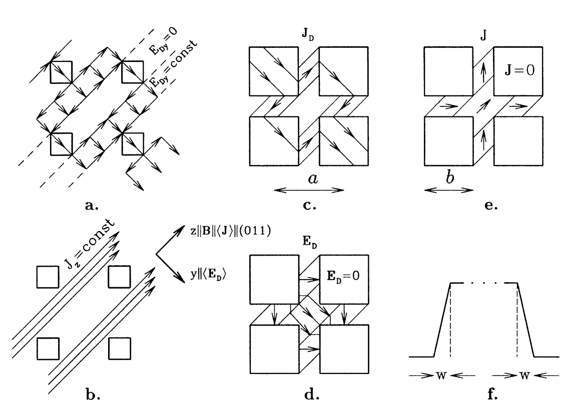

Fig. 2. (a) and (b): Local current and field pattern (schematic) for a square array of parallel, perfectly insulating, square-rod-shaped inclusions when $(0\,1\,1)\,\|\langle\boldsymbol{J}\rangle\|\boldsymbol{B}$ and $b < a/2 \equiv b_c$. (c)–(e) Similar drawings for the case $b > a/2 \equiv b_c$. (f) Trapezoidal ansatz used to describe the spatial dependence of fields and currents in the transition layers of width $\sim w \equiv a/|\mu\boldsymbol{B}|$. The symbols $\boldsymbol{E}_\mathrm{D}$, $\boldsymbol{J}_\mathrm{D}$ denote the dual electric field and flux, which are obtained by rotating $\boldsymbol{J}$ and $\boldsymbol{E}$, respectively, by 90° in the film plane at every point of the system. The asymptotic solution of the dual problem is used to find the asymptotic forms of $\boldsymbol{E}(\boldsymbol{r})$ and $\boldsymbol{J}(\boldsymbol{r})$ – details appear in Ref. [5].

other types of conducting hosts with more complicated magneto-transport properties, (e.g., both μ and the diagonal Ohmic resistivity ρ_0 may depend upon $|\boldsymbol{B}|$) will exhibit the same behavior for the relative bulk effective magneto-resistivity $\delta\rho_e/\rho_0$ as function of $\mu\boldsymbol{B}$, irrespective of those complications. More recently, it was shown that along the directions of high symmetry of the planar array, the behavior greatly simplifies at very strong fields $|\mu\boldsymbol{B}| \gg 1$. The asymptotic local current distribution can then be found explicitly, and explicit algebraic expressions were obtained for the asymptotic in-plane macroscopic resistivity components [4].

Along directions of high symmetry in such an array, there exist inclusion-free parallel layers or slabs, which span the system from end to end, if the inclusions have a sufficiently small lateral size b. For perfectly insulating inclusions, when $\boldsymbol{B}$, as well as the average current density $\langle\boldsymbol{J}\rangle$, lie along those slabs, the asymptotic current flow is entirely confined to those slabs, and is uniform there, when $|\mu\boldsymbol{B}| \gg 1$ – see Fig. 2(b), which shows the local current pattern for a square array of small cross-section insulating rods, when $(0\,1\,1)\,\|\langle\boldsymbol{J}\rangle\|\boldsymbol{B}$. The corresponding longitudinal magneto-resistance is then saturated and does not change upon further increase of $\boldsymbol{B}$. When there are no inclusion-free slabs along $\boldsymbol{B}$ and $\langle\boldsymbol{J}\rangle$, the asymptotic in-plane current follows a zig-zag pattern which is saturated when $|\mu\boldsymbol{B}| \gg 1$, and is still simple enough to be calculable in closed form when $\boldsymbol{B}$ and $\boldsymbol{J}$ point in a high symmetry direction, e.g., for the case $(0\,1\,1)\,\|\langle\boldsymbol{J}\rangle\|\boldsymbol{B}$ in a square array of large, square-cross-section rods, described in Fig. 2(e), the current density is uniform in the parallelogram-shaped regions outlined in the gaps between neighboring inclusions. By contrast, the current component along the columnar axis continues to increase as $|\boldsymbol{B}|$ without any saturation. Thus, even though the average current component in that direction vanishes in a thin film experiment, the local currents in that direction make the most important contribution to the total dissipation. This leads to a positive longitudinal magneto-resistance that increases as $\boldsymbol{B}^2$ without any saturation. Viewed as function of the inclusion size b, there is thus a drastic change in the macroscopic response when the inclusion-free slabs shrink to zero at $b = b_c$. This is caused by the drastic change in current flow pattern (cf. Figs. 2(b) and 2(e)). The drastic change in system behavior has many of the characteristics of a second order phase transition: (a) The macroscopic response is singular as $b \to b_c$ and $|\mu\boldsymbol{B}| \to \infty$. (b) Near that point, the macroscopic response exhibits scaling behavior as function of two physical lengths which tend to zero at the transition, namely $w \equiv a/|\mu\boldsymbol{B}|$ (a is the array period) and $b - b_c$ [5]. A similar behavior is also exhibited by the transverse magneto-resistance in the case of a periodic array of parallel inclusions that are perfect conductors. At the edges of the inclusion-free slabs in Fig. 2(b), or the parallelogram-shaped regions in Fig. 2(e), there appear thin transition layers, of thickness $\sim w$, where the current density changes rapidly between two very different values. As long as the system is not near the above mentioned threshhold, the transition layers do not contribute any extra dissipation to leading order in $|\mu \boldsymbol{B}|$. However, at the threshold their contribution becomes dominant, and leads to the scaling behavior described above. This can be treated approximately by using a simple trapezoidal ansatz for the in-plane current distribution when $|\mu \boldsymbol{B}| \gg 1$ (see Fig. 2(f) and Ref. [5]).

In trying to extend these properties to AC electrical or optical phenomena, a difficulty is encountered: A crucial requirement for developing the non-saturating behavior of magneto-resistance in the DC case, as well as the strong directional oscillations, was that the Hall-to-transverse Ohmic resistivity ratio, which is equal to $\mu|\boldsymbol{B}|$, be greater than 1 in the host constituent. In an optical composite, the host constituent must be a dielectric material, therefore the antisymmetric elements of its electric permittivity tensor $\hat{\varepsilon}$ will be small even in a very strong magnetic field. We proposed the following stratagem to overcome this difficulty: Instead of using a conventional homogeneous dielectric material as the host constituent, use a metal/dielectric composite that has a sharp quasi-static resonance in the vicinity of the operating frequency ω (see Fig. 3(a)). Near such a resonance, the transverse diagonal components $\varepsilon_\perp$ of $\hat{\varepsilon}$, as well as its antisymmetric off diagonal components ε_H, will pass through 0, when either ω or $\boldsymbol{B}$ are varied. However, this will occur, for $\varepsilon_\perp$ and ε_H, at slightly different values of ω and $\boldsymbol{B}$, especially when $|\mu \boldsymbol{B}|$ is large. Thus, by carefully adjusting ω, $\boldsymbol{B}$, and the microstructure, it should be possible to achieve large values of the ratio $\varepsilon_H/\varepsilon_\perp$ for such a composite host medium. In order to have sharp resonances, the microstructure should be either a dilute collection of identically shaped inclusions, or else it should have a periodic microstructure, as in Fig. 3(d). In that medium we could then embed a periodic array of inclusions, made of a conventional, homogeneous dielectric material, with unit cell and particle sizes that are much greater than those used in fabricating the composite host. In practice, this idea can be implemented by embedding a two-dimensional periodic array of columnar metallic inclusions in a conventional dielectric host, where the microstructure has at least two different characteristic length scales (see Figs. 3(b) and (c)). Numerical calculations show that such a microstructure will indeed lead to an in-plane bulk effective electric permittivity that has a strong dependence on both the magnitude and the direction of $\boldsymbol{B}$ (see Fig. 3(e)) [6]. Experimental tests of these predictions would be very desirable.

Another way to obtain interesting new types of optical response, under the influence of a magnetic field, is to make a periodic array of very small holes in a thin metal film. The uniform film is opaque to an incident electromagnetic wave, and the punctured film usually remains

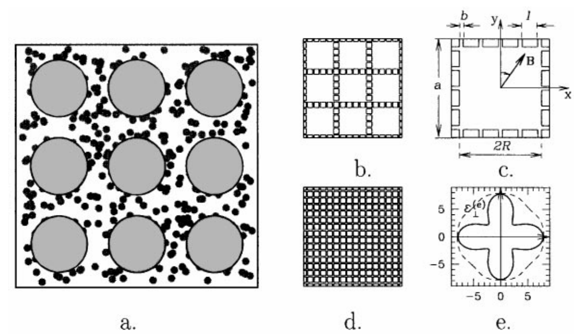

Fig. 3. (a) Idealized picture of a composite where the host is itself a composite medium made of a normal dielectric material with a random distribution of small metallic inclusions. Inside this composite host is embedded a periodic array of much larger normal dielectric inclusions. (b) A two-heterogeneity-length-scales periodic microstructure made of rows and columns of small, tightly spaced inclusions. (c) One square unit cell of the periodic microstructure used in our calculations: The small squares represent a cross section of the infinitely long metal rods that lie parallel to the z-axis. The size parameters were $l/a = 0.16$, $b/a = 0.04$, $R/a = 0.4$. The two important length scales in this system are b and $2R$, which differ by a factor 20. (d) Shows what the pure composite host would look like. (e) Polar plot of the bulk effective transverse electric permittivity $\varepsilon_\perp^{(e)}$ of the periodic composite shown in (b): solid line shows the real part, dashed line the imaginary part. The magnetic field $\boldsymbol{B}$ has a fixed magnitude, corresponding to $\mu|\boldsymbol{B}| = 5$, and is rotated in the x, y-plane. The angular frequency of the applied electric field is $\omega = 0.3\omega_p$, (ω_p is the plasma frequency of charge carriers in the metallic inclusions) and lies in the resonance region, where the ratio $\varepsilon_{xy}^{(e)}/\varepsilon_{xx}^{(e)}$ is large. The dielectric constant was taken to be 10 in the metal inclusions as well as in the dielectric host.

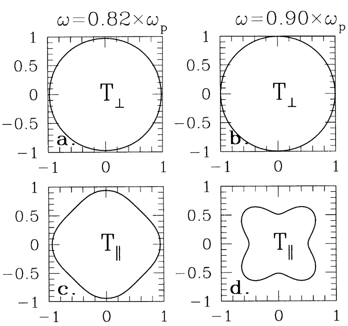

Fig. 4. Polar plots of the transmission coefficients $T_\perp$ and $T_\parallel$, obtained using the bulk effective electric permittivity tensor $\hat{\varepsilon}_e$, calculated numerically for a thin metallic film with a periodic square array of cylindrical holes with radius-to-lattice-parameter ratio $R/a = 0.2$, when a static magnetic field $\boldsymbol{B}$ is rotated in the film plane. The subscript $\perp$ corresponds to the polarization $\boldsymbol{E} \perp \boldsymbol{B}$, while the subscript $\parallel$ corresponds to the polarization $\boldsymbol{E} \parallel \boldsymbol{B}$. The in-plane field $\boldsymbol{B}$ has a fixed magnitude, corresponding to $\mu|\boldsymbol{B}| = 20$, the angular frequencies of the applied electric field are $\omega = 0.82\omega_p$ [(a) and (c)] and $\omega = 0.9\omega_p$ [(b) and (d)], and $\omega_p\tau = 40$, ω_p is the plasma frequency of charge carriers in the metal constituent (after Ref. [9]).

opaque if the hole sizes are less than the wavelength. Nevertheless, it was recently discovered that such a film exhibits a strong transmissivity when the frequency ω is near a so-called "surface plasmon resonance" [7,8].

We have found that, when a strong magnetic field $\boldsymbol{B}$ is applied in the film plane, the resonance gets shifted. Moreover, the frequency shift depends on both the magnitude and the direction of $\boldsymbol{B}$. Consequently, the transmissivity should become sensitive to those quantities. Calculations bear out those expectations [9] (see Fig. 4). Such sensitivity could form the basis for a new type of magneto-optical switch.

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