



Effects of Magnetic Field on Charge Carrier Transport in Semiconductor Devices

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Abstract

This methodology paper presents a compact framework for analyzing how an externally applied magnetic field modifies charge-carrier transport in semiconductor devices. The study combines a semiclassical Drude-Boltzmann conductivity-tensor model, Hall-effect analysis, a two-carrier extension, and literature-guided interpretation of geometric, inhomogeneity-driven, and quantum magnetoresistance. The magnetic-field response is evaluated through longitudinal conductivity, Hall conductivity, Hall angle, resistivity, and magnetoresistance as functions of carrier mobility, carrier density, compensation ratio, and field strength. Representative parameter sets are used for Si-like, GaAs-like, and InSb-like transport to demonstrate the sensitivity of device behavior to mobility. The model shows that magnetic deflection is weak in low-mobility silicon at moderate fields but becomes pronounced in high-mobility III-V semiconductors; at 1 T, the normalized longitudinal conductivity falls to approximately 58% for a GaAs-like mobility and about 6% for an InSb-like mobility. In an ideal one-carrier homogeneous Drude conductor this conductivity redistribution does not by itself produce longitudinal magnetoresistance, so measurable resistance changes require multicarrier transport, scattering-time dispersion, device geometry, inhomogeneity, space-charge effects, or quantum mechanisms. The proposed workflow is suitable for Hall devices, magnetic sensors, semiconductor/metal hybrid structures, and comparative magneto transport simulations while remaining consistent with literature published through 2018.

Introduction

Charge transport in a semiconductor is controlled by carrier density, effective mass, mobility, scattering time, electric-field distribution, and device geometry. When a magnetic field is applied, moving carriers experience the Lorentz force $q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$, which bends their trajectories and produces a transverse Hall field. The resulting rotation of the current density relative to the electric field can strongly alter measured voltage and current paths, particularly when the dimensionless product μB approaches or exceeds unity. This

condition is reached at comparatively low magnetic fields in narrow-gap, high-mobility semiconductors and two-dimensional electron systems, making magnetic-field transport important for Hall sensors, magnetoresistive sensors, read heads, and nanoscale electronic devices (Beenakker & van Houten, 1991; Solin et al., 2002).

The magnetic-field response is not described by a single mechanism. In a homogeneous one-band Drude model, the conductivity tensor changes substantially with field, while inversion of that

tensor gives a longitudinal resistivity that is ideally field independent. Real semiconductors nevertheless exhibit positive, nonlinear, or nearly linear magnetoresistance because they contain multiple carrier populations, distributions of mobility and scattering time, contact and geometry effects, spatial inhomogeneity, space-charge regions, or quantized electronic states. Herring (1960) established that random inhomogeneities can alter galvanomagnetic measurements, while later work showed that macroscopically disordered semiconductors can display large non-saturating magnetoresistance (Parish & Littlewood, 2003). In the quantum limit, Abrikosov (1998) provided a route to linear positive magnetoresistance when only a small number of Landau levels participate in transport.

Semiconductor technology therefore provides a useful platform in which classical, geometric, disorder-driven, and quantum magnetic-field effects can be compared using the same measured quantities. Solin et al. (2000) demonstrated extremely large room-temperature geometric magnetoresistance in InSb containing a metallic inhomogeneity, and Lee et al. (2002) linked linear magnetoresistance in silver chalcogenides with band-gap tuning and a change of Hall-sign behavior. Hu and Rosenbaum (2008) subsequently emphasized that both classical disorder and quantum mechanisms can generate large linear magnetoresistance. Silicon, although much lower in mobility than InSb, has also shown strong magnetoresistance under special space-charge, inhomogeneity, and geometric conditions (Delmo et al., 2009; Wan et al., 2011; Porter & Marrows, 2012). These results motivate a methodology that separates the basic Lorentz-force response from the additional mechanisms needed to explain a measured longitudinal resistance change.

The objective of this paper is to define such a methodology and demonstrate its use with representative semiconductor parameters. The analysis focuses on transverse magnetic fields, steady-state transport, and fields up to 2 T for the model calculations, while using the literature through 2018 to interpret high-field, geometric, and device-level behavior. The approach is intended as a reproducible methodology paper rather than a report of new experimental measurements.

Literature Review

Early galvanomagnetic theory recognized that nonuniform conductivity can mix Hall and longitudinal voltages. Herring (1960) derived

corrections produced by random inhomogeneities and provided a foundation for later disorder-based interpretations. For mesoscopic and nanoscale structures, Beenakker and van Houten (1991) reviewed diffusive, ballistic, edge-channel, and quantum Hall transport in semiconductor nanostructures, showing that magnetic fields can reorganize current into cyclotron trajectories and edge channels when the relevant length scales become comparable to the device dimensions.

A distinct high-field mechanism was proposed by Abrikosov (1998), who showed that gapless or narrow-gap systems in the quantum limit may exhibit positive magnetoresistance that is approximately linear in magnetic field. Experimental work then demonstrated large geometric responses in nonmagnetic semiconductors. Solin et al. (2000) embedded a conducting Au region in an InSb van der Pauw structure and showed that magnetic deflection redirected current around the metal, producing a very large resistance increase. The device implication was developed further by Solin et al. (2002), who fabricated an InSb quantum-well magnetoresistive sensor for high-density magnetic recording.

Linear magnetoresistance also emerged in disordered or compensated semiconductor systems. Lee et al. (2002) observed a strong relationship among band structure, Hall coefficient sign, and linear magnetoresistance in silver chalcogenides. Parish and Littlewood (2003) modeled a strongly inhomogeneous semiconductor as a network of regions with different local mobilities and showed that disorder can generate non-saturating, quasi-linear magnetoresistance without requiring a magnetic material. Hu and Rosenbaum (2008) compared this classical route with a quantum route in InSb, highlighting the importance of mobility, disorder, and carrier concentration in determining which mechanism dominates.

The same concepts were later demonstrated in silicon. Delmo et al. (2009) reported large positive magnetoresistance in lightly doped Si under space-charge-limited conduction, where field-dependent carrier motion and electric-field inhomogeneity became important. Wan et al. (2011) showed that geometric design could enhance low-field silicon magnetoresistance, whereas Porter and Marrows (2012) attributed linear magnetoresistance in n-type silicon to doping-density fluctuations and current-path deformation. Sun and Kosel (2013) reviewed semiconductor/metal extraordinary magnetoresistance and identified semiconductor

mobility, conductivity contrast, interface quality, and device geometry as the dominant design variables. By 2018, high-quality thin InSb films with room-temperature electron mobility near

$3.9 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ had been demonstrated, supporting continued interest in high-mobility III-V layers for magnetic sensing and transport devices (Kang et al., 2018).

Table 1. Representative literature relevant to magnetic-field-dependent semiconductor transport

Reference	Focus	Relevance to present methodology
Herring (1960)	Random inhomogeneity	Galvanomagnetic measurements can be altered by spatial conductivity fluctuations.
Abrikosov (1998)	Quantum limit	Linear positive magnetoresistance can arise from quantum-limit transport.
Solin et al. (2000)	InSb/Au geometry	Lorentz-force current deflection can create very large geometric magnetoresistance.
Parish & Littlewood (2003)	Disordered semiconductor	Mobility disorder can produce non-saturating, quasi-linear magnetoresistance.
Hu & Rosenbaum (2008)	InSb	Classical-disorder and quantum routes can both yield linear magnetoresistance.
Wan et al. (2011)	Silicon geometry	Device geometry can amplify low-field magnetoresistive response.
Sun & Kosel (2013)	Semiconductor/metal hybrids	Mobility, geometry, conductivity contrast, and contacts govern EMR performance.

Methodology

The methodology is organized as a sequence of physical assumptions, parameter definition, tensor calculation, derived transport metrics, and sensitivity comparison. The workflow is designed so that the basic semiclassical response can be evaluated first and additional mechanisms can then be introduced only when required by the observed resistance behavior.

1. Device and field configuration

A rectangular semiconductor channel is considered with current applied along the x-

direction and a uniform magnetic field B applied perpendicular to the channel plane (z-direction). The transverse y-direction is used for the Hall voltage. Contacts are assumed ohmic, and the initial calculation assumes steady-state, low-frequency transport with spatially uniform material parameters. The configuration corresponds to a Hall bar or the active semiconductor region of a magnetoresistive device. Figure 1 illustrates the carrier deflection and Hall-voltage formation.

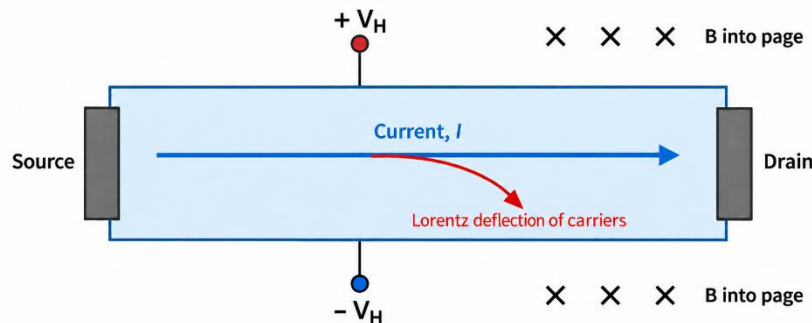


Figure 1. Conceptual magnetic-field action on charge carriers in a semiconductor channel.

2. Semiclassical transport equations

For a single carrier type with mobility μ , zero-field conductivity $\sigma_0 = nq\mu$, and B perpendicular

to the current plane, the Drude conductivity tensor is represented by $\sigma_{xx} = \sigma_0/[1 + (\mu B)^2]$ and $|\sigma_{xy}| = \sigma_0\mu B/[1 + (\mu B)^2]$. The Hall angle is $\theta_H = \tan^{-1}(\mu B)$. These relations directly quantify the

magnetic deflection of current. The characteristic crossover occurs near $\mu B = 1$, at which $\theta H = 45^\circ$ and the longitudinal conductivity component is half of its zero-field value.

The resistivity tensor is obtained from matrix inversion: $\rho_{xx} = \sigma_{xx}/(\sigma_{xx}^2 + \sigma_{xy}^2)$ and $\rho_{xy} = -\sigma_{xy}/(\sigma_{xx}^2 + \sigma_{xy}^2)$. In the ideal homogeneous one-carrier Drude model, ρ_{xx} reduces to $1/\sigma_0$ and therefore has no magnetoresistance. This result is used as a diagnostic baseline: if a real device exhibits finite magnetoresistance, at least one assumption of the ideal one-carrier model must be relaxed.

3. Two-carrier extension and magnetoresistance

To represent electron-hole coexistence or partial compensation, electron and hole contributions are summed before inversion. The conductivity components are $\sigma_{xx}(B) = e[n\mu_n/(1 + (\mu_n B)^2) + p\mu_p/(1 + (\mu_p B)^2)]$ and $\sigma_{xy}(B) = eB[p\mu_p^2/(1 + (\mu_p B)^2) - n\mu_n^2/(1 + (\mu_n B)^2)]$. From the resulting $\rho_{xx}(B)$, magnetoresistance is calculated as $MR(\%) = [\rho_{xx}(B) - \rho_{xx}(0)]/\rho_{xx}(0) \times 100$. In the fully compensated limit $n = p$, the model gives the useful relation $\rho_{xx}(B)/\rho_{xx}(0) = 1 + \mu_n \mu_p B^2$, showing why high mobilities and multicarrier balance can strongly enhance the field response.

4. Parameter sets and simulation steps

Three representative mobility regimes are used: Si-like electron mobility $\mu_n = 0.135 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$, GaAs-like $\mu_n = 0.85 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$, and InSb-like $\mu_n = 3.93 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$. The InSb value is aligned with the approximately $39,290 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ mobility reported for a 100 nm InSb film by Kang et al. (2018); the Si-like and GaAs-like values are representative model inputs chosen for regime comparison rather than measurements of a specific sample. For the illustrative compensated two-carrier calculation, hole mobilities of 0.045, 0.040, and 0.080 $\text{m}^2 \text{ V}^{-1} \text{ s}^{-1}$ are assigned to the Si-, GaAs-, and InSb-like cases, respectively.

The numerical procedure is: (1) define carrier density and mobility parameters; (2) sweep B from 0 to 2 T; (3) calculate σ_{xx} and σ_{xy} ; (4) invert the tensor to obtain ρ_{xx} and ρ_{xy} ; (5) compute θH and MR ; (6) repeat for each mobility regime; and (7) compare the model trend with established mechanisms in the literature. Where the one-carrier model predicts negligible MR but experiment shows a large response, the analysis should next test multicarrier transport, mobility distributions, geometric current-path distortion, space-charge effects, or quantum-limit transport, consistent with the mechanisms reported by Herring (1960), Abrikosov (1998), Parish and Littlewood (2003), and Delmo et al. (2009).

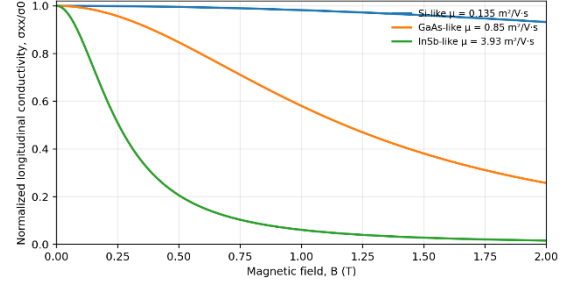


Figure 2. Model prediction of normalized longitudinal conductivity for three representative mobility regimes.

5. Validation and interpretation criteria

The methodology separates numerical consistency from physical interpretation. First, σ_{xx} and σ_{xy} must recover σ_0 and zero Hall voltage as B approaches zero. Second, the Hall angle must follow the sign and magnitude expected from the dominant carrier. Third, MR should vanish for a strictly homogeneous one-carrier constant-mobility model; nonzero MR must therefore be linked to an added physical or geometric mechanism. Finally, predicted trends should be compared with the established experimental signatures: geometric current deflection in InSb hybrids (Solin et al., 2000; Sun & Kosel, 2013), non-saturating disorder-driven behavior (Parish & Littlewood, 2003; Porter & Marrows, 2012), quantum linear magnetoresistance (Abrikosov, 1998; Hu & Rosenbaum, 2008), and space-charge or geometry-enhanced silicon responses (Delmo et al., 2009; Wan et al., 2011).

Results

The model demonstrates that mobility controls the field scale at which magnetic deflection becomes important. At $B = 1 \text{ T}$, the Si-like case retains about 98.2% of its zero-field longitudinal conductivity and has a Hall angle of only 7.7° . The GaAs-like case retains about 58.1% and reaches a Hall angle of 40.4° , placing it near the $\mu B \approx 1$ crossover. The InSb-like case retains only about 6.1% of the longitudinal conductivity component and reaches a Hall angle of 75.7° , indicating that current is strongly rotated from the electric-field direction. These values explain why high-mobility narrow-gap semiconductors are particularly responsive in Hall and geometric magnetoresistive devices.

When the compensated two-carrier extension is applied, the model yields a finite positive longitudinal magnetoresistance. Under the illustrative mobility assumptions, MR at 1 T is approximately 0.61% for the Si-like case, 3.4% for the GaAs-like case, and 31.4% for the InSb-like case; at 2 T the corresponding values rise to

roughly 2.43%, 13.6%, and 125.8%. The quadratic trend follows the compensated relation $\mu n \mu p B^2$. These values are not intended to reproduce any one experiment; they

demonstrate how multicarrier balance converts magnetic deflection into a measurable longitudinal resistance increase.

Table 2. Model-generated transport response for representative semiconductor mobility regimes

Regime	μn ($\text{m}^2/\text{V}\cdot\text{s}$)	σ_{xx}/σ_0 at 1 T	θ_H at 1 T	MR at 1 T*	MR at 2 T*
Si-like	0.135	98.2%	7.7°	0.61%	2.43%
GaAs-like	0.85	58.1%	40.4°	3.40%	13.60%
InSb-like	3.93	6.1%	75.7°	31.44%	125.76%

*Compensated two-carrier illustration ($n = p$) using $\mu p = 0.045$, 0.040 , and $0.080 \text{ m}^2/\text{V}\cdot\text{s}$, respectively.

The results also clarify why the very large magnetoresistance reported in some semiconductor devices cannot be explained solely by the ideal one-carrier Drude equations. The extreme geometric response reported for InSb/Au structures by Solin et al. (2000) arises because the field redirects current between semiconductor and metallic regions. Likewise, the large silicon responses reported by Delmo et al. (2009), Wan et al. (2011), and Porter and Marrows (2012) require space-charge, geometry, or spatial inhomogeneity. The present baseline model is therefore useful because it identifies when additional physical structure must be introduced rather than forcing an empirical resistance-field curve into a one-carrier theory.

Conclusion and Discussion

This paper developed a stepwise methodology for evaluating the effect of magnetic field on charge-carrier transport in semiconductor devices. The central variables are carrier mobility, carrier density, magnetic field, compensation, and device geometry. A conductivity-tensor calculation provides the longitudinal and Hall responses, while tensor inversion gives the measurable resistivities. The Hall angle $\theta_H = \tan^{-1}(\mu B)$ provides a compact measure of magnetic deflection and shows that high-mobility materials enter the strongly field-dependent regime at much lower magnetic fields than low-mobility materials. The model-generated comparison shows that an InSb-like semiconductor can experience a pronounced redistribution of current at 1 T, whereas a Si-like semiconductor remains close to its zero-field longitudinal conductivity. However, conductivity redistribution must not be confused with longitudinal magnetoresistance: in the ideal one-carrier homogeneous Drude model, ρ_{xx} is field independent. Finite MR appears when additional mechanisms are present, including electron-hole compensation, a distribution of scattering times

or mobilities, geometric current-path distortion, material inhomogeneity, space-charge effects, or quantum-limit transport. This interpretation is consistent with the historical progression from inhomogeneity theory (Herring, 1960), quantum magnetoresistance (Abrikosov, 1998), geometric InSb devices (Solin et al., 2000), disorder models (Parish & Littlewood, 2003), and later silicon and semiconductor/metal devices (Wan et al., 2011; Sun & Kosel, 2013). For practical device studies, the recommended next step is to combine the present tensor model with finite-element electrostatic/current-flow simulation using the actual device geometry and measured mobility versus temperature. Experimental validation should employ four-terminal longitudinal voltage, transverse Hall voltage, magnetic-field reversal to remove contact offsets, and temperature-dependent measurements to separate classical and quantum contributions. The methodology is therefore suitable as a foundation for studying Hall sensors, magnetoresistive semiconductor devices, semiconductor/metal hybrids, and high-mobility thin films such as the InSb structures reported by Kang et al. (2018).

References

- Herring, C. (1960). Effect of random inhomogeneities on electrical and galvanomagnetic measurements. *Journal of Applied Physics*, 31(11), 1939–1953. <https://doi.org/10.1063/1.1735477>
- Beenakker, C. W. J., & van Houten, H. (1991). Quantum transport in semiconductor nanostructures. *Solid State Physics*, 44, 1–228. [https://doi.org/10.1016/S0081-1947\(08\)60091-0](https://doi.org/10.1016/S0081-1947(08)60091-0)
- Abrikosov, A. A. (1998). Quantum magnetoresistance. *Physical Review B*, 58(5), 2788–2794. <https://doi.org/10.1103/PhysRevB.58.2788>
- Solin, S. A., Thio, T., Hines, D. R., & Heremans, J. J. (2000). Enhanced room-temperature geometric

magnetoresistance in inhomogeneous narrow-gap semiconductors. *Science*, 289(5484), 1530–1532.

<https://doi.org/10.1126/science.289.5484.1530>

Lee, M., Rosenbaum, T. F., Saboungi, M.-L., & Schnyders, H. S. (2002). Band-gap tuning and linear magnetoresistance in the silver chalcogenides. *Physical Review Letters*, 88(6), 066602.

<https://doi.org/10.1103/PhysRevLett.88.066602>

Solin, S. A., Hines, D. R., Rowe, A. C. H., Tsai, J. S., Pashkin, Y. A., Chung, S. J., Goel, N., & Santos, M. B. (2002). Nonmagnetic semiconductors as read-head sensors for ultra-high-density magnetic recording. *Applied Physics Letters*, 80(21), 4012–4014.

<https://doi.org/10.1063/1.1481238>

Parish, M. M., & Littlewood, P. B. (2003). Non-saturating magnetoresistance in heavily disordered semiconductors. *Nature*, 426(6963), 162–165. <https://doi.org/10.1038/nature02073>

Hu, J., & Rosenbaum, T. F. (2008). Classical and quantum routes to linear magnetoresistance. *Nature Materials*, 7(9), 697–700. <https://doi.org/10.1038/nmat2259>

Delmo, M. P., Yamamoto, S., Kasai, S., Ono, T., & Kobayashi, K. (2009). Large positive magnetoresistive effect in silicon induced by the space-charge effect. *Nature*, 457(7233), 1112–1115. <https://doi.org/10.1038/nature07711>

Wan, C., Zhang, X., Gao, X., Wang, J., & Tan, X. (2011). Geometrical enhancement of low-field magnetoresistance in silicon. *Nature*, 477(7364), 304–307. <https://doi.org/10.1038/nature10375>

Porter, N. A., & Marrows, C. H. (2012). Linear magnetoresistance in n-type silicon due to doping density fluctuations. *Scientific Reports*, 2, 565. <https://doi.org/10.1038/srep00565>

Sun, J., & Kosel, J. (2013). Extraordinary magnetoresistance in semiconductor/metal hybrids: A review. *Materials*, 6(2), 500–516. <https://doi.org/10.3390/ma6020500>

Kang, S. S., Park, S. I., Shin, S. H., Shim, C.-H., Choi, S.-H., & Song, J. D. (2018). High-quality 100 nm thick InSb films grown on GaAs(001) substrates with an In_xAl_{1-x}Sb continuously graded buffer layer. *ACS Omega*, 3(11), 14562–14566. <https://doi.org/10.1021/acsomega.8b02189>