Evaluation of Transport Properties Using Quantitative Mobility Spectrum Analysis

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Hall effect measurements are the most commonly used method for determining the carrier type, concentration, resistivity, and mobility of semiconductor materials. Measurements made at a single applied field usually provide enough information to characterize transport properties of single carrier semiconductors. Variable field measurements provide the data needed to characterize semiconductor materials with multiple populations of distinct carrier species such as quantum wells, multilayer device structures (i.e. heterostructures), HBTs and HEMTs—by acquiring detailed information about transport properties of the *individual* carriers that make up a multi-carrier material. This is important for both research and development of new materials and industrial characterization and process control.

This article looks at the use of the Quantitative Mobility Spectrum Analysis (QMSA) of magnetic field-dependent Hall data to characterize transport properties of multilayer semiconductor structures. We also comment on the use of QMSA to characterize novel materials fabricated in R&D environments and to evaluate deposition products in quality control applications.

Hall Effect Measurements

Single field Hall effect measurements provide only the Hall coefficient and a weighted average of mobilities of all available carriers at the measurement temperature. Data collected include the measurement temperature, applied magnetic field (B), Hall coefficient (R_H) and resistivity (ρ), from which the mobility and density (or concentration) can readily be measured. Because both of these measurements refer only to the bulk average of all available carriers that make up the material, this data is of limited value. Furthermore, in the absence of measurements at other applied fields, it is impossible to determine whether more than one carrier species is present in the sample.

The measurement of Hall data from variable fields can provide additional information about multiple carrier semiconductors. Figure 1 shows the Hall coefficient and resistivity as a function of field for three different samples. Although the raw data does not allow extraction of any individual carrier's behavior, it may be used to distinguish one material from another. In Figure 1a, the R_H vs. B plots suggest that samples A and B are similar, while C is dissimilar. And in fact, A and B are closely related structures. In Figure 1b, the resistivity data show that samples A and B differ in conductance, although more specific

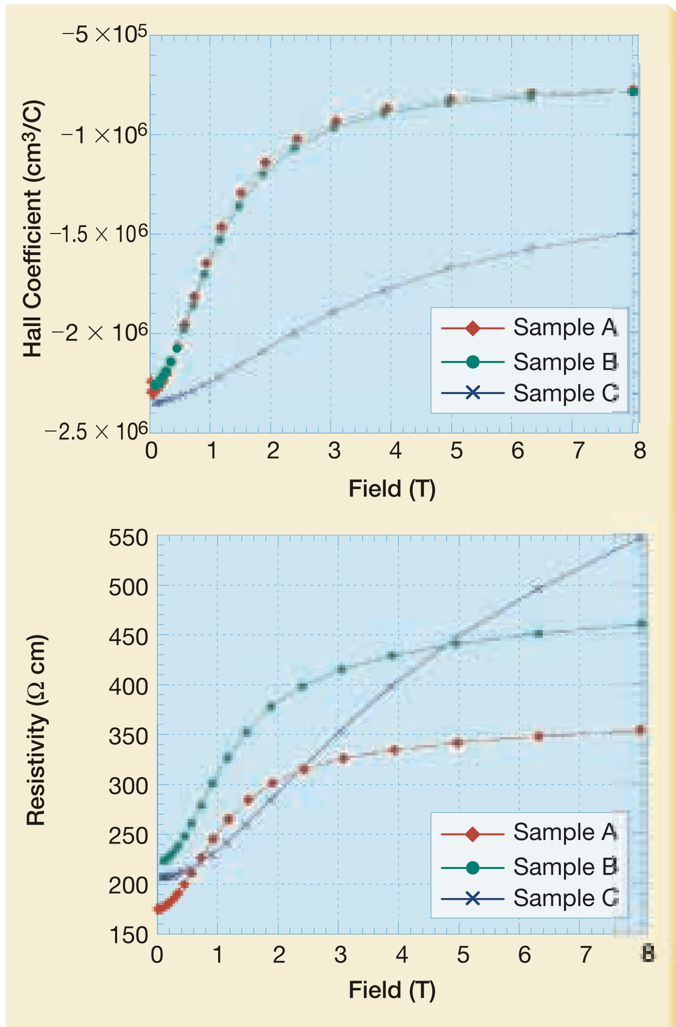

Figure 1. (a) Hall coefficient and (b) resistivity dependence on applied field for semiconductors with multi-carrier behavior. The raw data from Hall and resistivity measurements distinguishes different materials but does not reveal individual carrier behavior—a more sophisticated analysis such as quantitative mobility spectrum analysis (QMSA) is required.

QMSA Results for Hall Data Presented in Figure 1.

Sample ID	Mobility 1 (cm^2/Vs)	Density 1 (cm^{-3})	Mobility 2 (cm^2/Vs)	Density 2 (cm^{-3})
Sample A	−1948	7.111e+12	−20538	1.067e+12
Sample B	−1609	6.767e+12	−17424	9.010e+11
Sample C	−1723	1.797e+12	−12826	2.051e+12

Table 1. Electron mobilities extracted by applying QMSA to the Hall data shown in Figure 1.

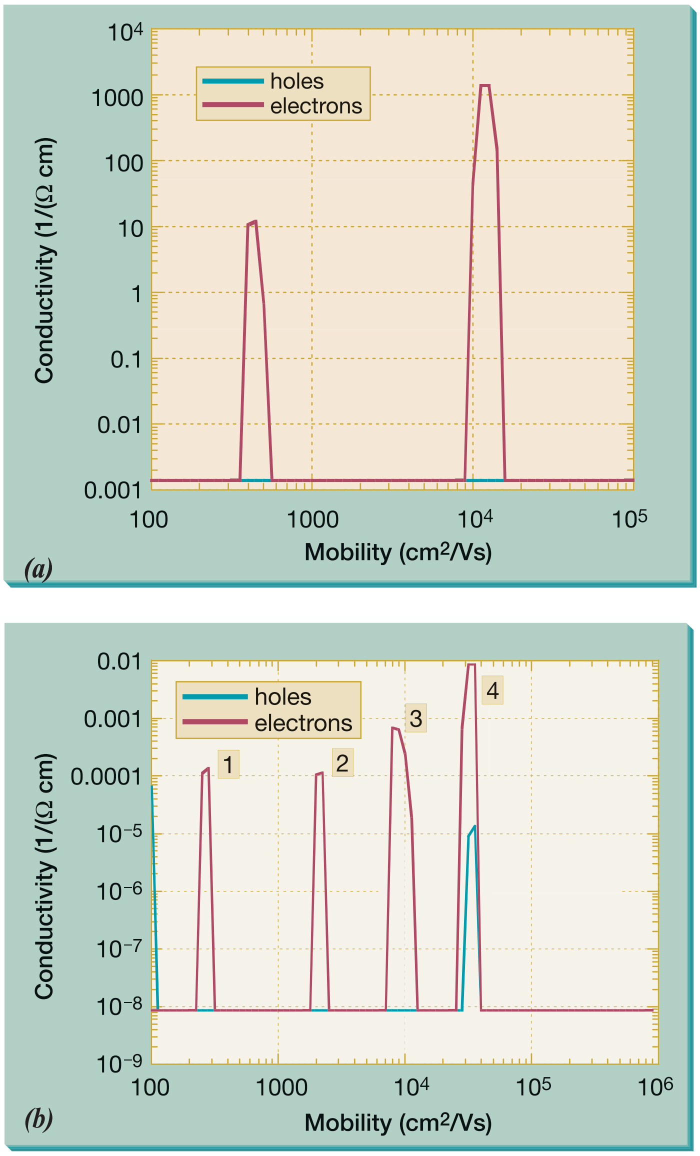

Figure 2. (a) Mobility spectrum calculated for the two carrier case for an InP PHEMT and (b) for a GaAs PHEMT sample. For the latter, the two high mobilities are due to 2DEG carriers in the QW channel layer (designated e Carrier 3 and 4), and the existence of two peaks suggests that two sub-bands in the QW layer are occupied.

characteristics cannot be inferred. Thus, Hall coefficient and resistivity measurements provide general qualitative information about multi-carrier samples but do not identify individual carrier properties. To correctly characterize transport properties, a more sophisticated analysis, known as Mobility Spectrum Analysis, is required.

Quantitative Mobility Spectrum Analysis

Mobility Spectrum Analysis was developed by Beck and Anderson in 1987 [1] and was further expanded to Quantitative Mobility Spectrum Analysis (QMSA) by Meyer and Hoffman [2] of the Naval Research Laboratory and Antoszewski et al [3, 4] at the University of Western Australia in 1997. Lake Shore licensed the analytic method, and developed a QMSA software calculation package for use with its own Hall effect measurement systems [5]. This software may also be used to analyze Hall effect data from other systems. Due to the nature of the analysis, however, QMSA results are very sensitive to inherent R_H and ρ measurement errors, so that a high performance system such as the Lake Shore 7500 or 9500 series is required for the most reliable results.

In essence, QMSA correlates the measured Hall coefficient and resistivity to a unique mobility spectrum. The Hall coefficient and resistivity measurements in different applied magnetic fields are analyzed to extract a corresponding set of carrier mobilities and concentrations. QMSA takes as its input values the measured Hall coefficient and resistivity at various values of magnetic field. The elements of the field-dependent conductivity matrix are then calculated, and by numerically fitting these elements, QMSA is able to extract a spectrum of mobilities and densities for the individual carriers.

QMSA can be used to demonstrate that samples A and B contain low mobility carriers (see Table 1: Mobility 1, Density 1) with mobilities of -1948 and -1609 cm^2/V s respectively. Samples A and B also both have high mobility carriers (denoted Mobility 2, Density 2) with values of approximately $-20{,}000$ cm^3/V s, and densities of roughly $1 \times 10^{12}/cm^3$ in both samples.

The structure of sample C appears to be entirely distinct from that of these two samples, evidenced by the fact that its high mobility carrier is far less mobile than those of sample A and B, while being present at twice the concentration. These findings suggest that samples A and B are very similar in the identity and concentration of their high mobility carriers, and different with regards to their low mobility carriers. The identity and concentration of carriers in sample C differ from those in both samples A and B. These findings demonstrate the advantage of QMSA in characterizing multi-carrier materials, in contrast to the limited information available from the characterization depicted in the results of Figure 1.

Multi-Carrier Semiconductor Materials

QMSA can be used to analyze the carrier properties for single- and multi-carrier devices. Figure 2 show QMSA results for Hall effect measurement data collected from (a) an InP-based PHEMT and (b) a GaAs PHEMT sample. In Figure 2a, two electron carriers have been identified with mobilities of -427 cm^2/V s and $-12{,}018$ cm^2/V s and densities of $3.372 \times 10^{17}/cm^3$ and $1.533 \times 10^{18}/cm^3$, respectively. The high mobility peak is due to the 2DEG (two dimensional electron gas) carrier in the QW channel layer. The low mobility peak is due to a carrier in a highly-doped layer such as the cap layer.

Figure 2b shows the results for a GaAs PHEMT structure, with the QMSA spectrum revealing that four distinct electron carriers and a single hole populate this heterostructure device. The mobilities and densities of each carrier are given in Table 2. These mobility spectra clearly show the multi-carrier, mixed conduction nature of this sample. There are four electron peaks in Figure 2b. The two peaks at higher mobility are due to 2DEG carriers in the QW channel layer (designated e Carrier 3 and 4). In addition, the existence of two peaks suggests that two sub-bands in the QW layer are occupied.

The lowest mobility peak (e Carrier 1) is due to a carrier in the cap layer, while the intermediate mobility peak (designated e Carrier 2) is most likely to be due to a defect-induced carrier in a buffer layer, or an interface/surface carrier. The existence of this carrier implies poor device quality, and demonstrates the power of QMSA as a diagnostic tool for defect detection.

Although not shown here, the mobility of the 2DEG carriers is strongly temperature dependent and suggests thermally activated scattering dominant charge transport. This dependence has been observed in all PHEMT devices studied thus far using QMSA. Conversely, the mobility of the cap layer carriers are virtually temperature independent, suggesting electron-impurity scattering dominant charge transport [6].

Carrier mobilities and densities for the pseudomorphic HEMT device.

	Mobility 1 (cm^2/Vs)	Density ($1/cm^3$)
e Carrier 1	−269.07	-5.8436×10^{12}
e Carrier 2	−2129.1	-6.53059×10^{11}
e Carrier 3	−8674.5	-1.14425×10^{12}
e Carrier 4	−33436	-3.35793×10^{12}
hole Carrier	34043	4.07967×10^{9}

Table 2. Carrier mobilities and concentrations for the case of a multi carrier PHEMT device. The lowest mobility comes from a defect-induced carrier in a buffer layer or the cap layer.

Conclusions

Quantitative Mobility Spectrum Analysis of variable field Hall effect measurements extracts significantly more information for electron transport characterization of semiconductor materials with multiple carrier species than is possible from single field Hall measurements alone, which determines only the bulk mobility and carrier concentration. QMSA is able to extend the data into studies of the individual carrier mobilities and concentrations for all carriers that comprise the material.

As an in-line metrology tool, QMSA allows the design of QA/QC procedures that will test the quantity of interest (e.g. the mobility and concentration of the high mobility electron carrier) in post-epitaxial products. This test procedure detects defective product early in the production cycle and prior to investment of additional capital in the wafer, and thus increases the yield. Testing may be performed on the wafer level and after dicing/slicing. Additionally, characterization of the 2DEG carrier mobility allows better estimation of the modeling parameters to be used in IC package design resulting in optimized performance, thus facilitating the efforts of the design engineer. Such measurements and analysis are also useful in fundamental research and development of novel heterostructures and HEMT devices.

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