Applied Surface Science 254 (2008) 6736–6741

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Charge transport diagnosis by: *I–V* (resistivity), screening and Debye length, mean free path, Mott effect and Bohr radius in InAs, $In_{0.53}Ga_{0.47}As$ and GaAs MBE epitaxial layers

Andrzej Wolkenberg *, Tomasz Przesławski

Institute of Electron Technology, al.Lotników 32/46, 02-668 Warsaw, Poland

ARTICLE INFO

Article history:
Received 18 February 2008
Received in revised form 15 April 2008
Accepted 15 April 2008
Available online 23 April 2008

PACS:
71.30.+th
71.55.Eg
72.10.−d

Keywords:
Hydrogenic donor
Impurity states
Mott concentration
Variable-range hopping
Nonmetal–metal transition

ABSTRACT

We propose using collected galvano-magnetic data on MBE samples of n-type undoped epi-layers of InAs, $In_{0.57}Ga_{0.47}As$ and GaAs on InP semi-insulating and GaAs semi-insulating substrates to characterize their charge transport properties. Hall concentration and resistance measurements vs. temperature were carried out, and these results allowed us to calculate the mean free path and magnetic length. However, they are mono-crystalline, they present multi-component charge transport structures. The characterization of these layers by means of a combined analysis of galvano-magnetic properties, *I–V* (resistivity), screening and Debye length, mean free path, Mott effect and Bohr radius characteristics gave new and very interesting results.

The application of a previously described method of analysis also allows for the presence of a Mott transition to be determined. The presence of a Mott transition leads to the hypothesis that a part of conductance in such layers, especially at low temperatures may be due to an impurity band.

We suppose either that during their epitaxial growth all of the investigated layers were unintentionally doped with excess atoms of one component, vacancies of other or that dangling bonds are present. Therefore, in the range of low temperatures, the possible and dominant conduction mechanism is conduction via such defects, with electrons moving by thermally activated hopping.

1. Introduction

By increasing the concentration of hydrogenic-like donors in a semiconductor, their binding energy decreases due to interactions between the donors. At sufficiently high concentrations of donor-like atoms, the binding energy vanishes and the electronic properties of the semiconductor change from those of the nonmetallic to the metallic phase. This phenomenon is known as the nonmetal–metal transition (NMT) or Mott transition. The Mott insulator transition has drawn the interest of both atomic and condensed matter physicists due to the possibilities it creates for simulating ideal, controlled condensed matter systems [1]. Under the correct circumstances the transition could be used to create supersolids or other novel phases of matter [2]. This problem exists for many years, and now with the finding of Bose fluids, many authors have published interesting results [3–13].

The critical donor concentration (Mott concentration) n_C is given by [3]:

$$n_C^{1/3} a_B \cong 0.26 \pm 0.05 \tag{1}$$

where a_B is the effective Bohr radius of an isolated hydrogenic donor.

Mott [4–6] proposed that an electron bound to a hydrogen-like donor was released when the screening length λ_S is in a specific relationship with the effective Bohr radius. Therefore, we want to include a treatment of the λ_S value in the characterization procedure of the investigated semiconductors.

In metals the screening length is given by the Thomas–Fermi type relation for degenerate electronic systems [3–6], which we adopt to our samples:

$$\lambda_S\,(\text{Å}) = 10^8 \sqrt{\frac{\varepsilon_r \varepsilon_0 E_F}{6\pi n e^2}} \tag{2}$$

where ε_r is the dielectric permitivity of semiconductor, ε_0 the permitivity of vacuum = 8.854×10^{14} (F/cm), E_F the Fermi level = (1 eV = 1.60219×10^{-19} J), n the electron concentration (cm^{-3}), and e is the electron charge = 1.60219×10^{-19} (C), and

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* Corresponding author. Tel.: +48 22 6460877.
E-mail address: wolken@ite.waw.pl (A. Wolkenberg).

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doi:10.1016/j.apsusc.2008.04.061

for semiconductors it is more proper to use the Debye length.

$$\lambda_D\,(\text{Å}) = 10^8 \sqrt{\frac{\varepsilon_r \varepsilon_0 kT}{4\pi n e^2}} \tag{2a}$$

where k is the Boltzman constant =1.38×10^{-23} J K^{-1}.

Thin MBE InAs, $In_{0.57}Ga_{0.47}As$ and GaAs epitaxial films are frequently used in construction of opto-electronic devices and magnetic sensors. A charge carrier transport study at 300 K and below (300–4 K) constitutes the fundamental instrument in the characterization of such layers. In doped semiconductors, impurities produce deep centers until the point at which a Mott transition is generated between the wave functions of the electrons trapped in the centers, such that they are distributed along the entire length of the semiconductor. At that point, local variations in the electric charge density disappear along with recombination by multiple phonon emission [7].

In earlier papers [14–18] it has been mentioned that semiconducting materials exhibit the magneto-resistance (MR) effect. The origins of MR and negative MR in thin semiconductor epitaxial layers may be connected with different coexisting transport mechanisms and different unintentionally present atoms [16,18–20]. At low temperatures and in the presence of a magnetic field it is possible that the spins from unintentionally doped atoms form a parallel configuration, which results in a strong increase in conductivity. Another interpretation is the presence of compressive epitaxial strain in thin films [21,22] with lattice mismatch. Our hypotheses were previously described in [22–30] and this paper is the third part of the published continuation [29,30] cataloging our efforts to describe transport parameters in thin MBE-grown semiconducting epi-layers using numerical solution of the neutrality equation and numerical calculations of resistivity and mobility.

The aim of this paper is to show the consequence of these calculations for the determination of further parameters vs. temperature, which can be a part of more reliable characterization of epi-MBE layers, e.g.: screening length, mean free path, Mott transition possibility and Bohr radius.

The mean free path l (see Eq. (3)) in semiconductors is a measure of their physical and electrical quality. The dependence of the mean free path on temperature in metals such as Cu or Ag has the form of $l \propto (1/T)$ [31]. The mean free path decreases with increasing temperature. The theory of the mean free path involves two parameters: the concentration n of free electrons, which is assumed to be on the same order as the number of atoms per unit volume, and the resistivity ρ of the layer. The mean free path l of the electrons is then determined from a comparison between theory and experiment.

We assume that in the case of semiconductors the formula (1) describing the mean free path remains valid, however, this time the concentration n of free electrons is on the order of the concentration of ionized donor atoms. As far as the electrical resistivity ρ_0 is concerned, we assume that the mean free path l may be described according to the Sommerfeld theory [31]:

$$l = \frac{h(3/8\pi)^{1/3}}{\rho n^{2/3} {q_0}^2}; \tag{3}$$

where h is the Planck's constant, 6.625×10^{-27} erg, ρ the resistivity, $\Omega\,\text{cm}/9 \times 10^{11}$ and q_0 is the electron charge, 4.802×10^{-10} esu.

On substituting the numerical values for h and q_0 we obtain the following equation:

$$l\,(\text{Å}) = 10^8 \frac{1}{7.1 \times 10^7 \rho n^{2/3}} \tag{3a}$$

We suppose, after Mott [21] that dangling bonds are present in the semiconductor samples therefore, in the lowest temperature range, conduction via impurities is the dominant mechanism, and electrons are thus moving by thermally activated hopping. This is based on the assumption that the density of states near the Fermi level is constant [32]. If this is a correct explanation, we should expect a linear plot of $\ln(\rho)$ against $1/T^{1/4}$. Mott [21] suggests the following dependence:

$$\rho = \rho_0 \exp\left[\left(\frac{T_0}{T}\right)^{1/4}\right] \tag{4}$$

where ρ_0 is the resistivity of a perfect structure and T_0 is the characteristic temperature, which is the slope of the Mott (4) plot.

This equation is a representation of existing charge transport behavior for the temperature-dependence of resistivity due to variable-range hopping (VRH) [21,22].

Our experiments revealed that the mean free path in the InAs, $In_{0.57}Ga_{0.47}As$ and GaAs MBE layers with good quality increases with temperature at low temperatures and then decreases at higher temperatures. These layers exhibit a positive magneto-resistance (PMR) effect. There are, however, some layers in which the mean free path l increases with temperature over the whole range of the investigated temperatures. This effect is connected with negative magneto-resistance (NMR) at low temperatures. We believe that the effect results from the presence of Mott's impurity levels ($\ln(\rho) \propto 1/T^4$ law).

2. Experimental

The characterized samples are layers of InAs on GaAs, $In_{0.53}Ga_{0.47}As$ on InP SI and GaAs on GaAs and are grown in a RIBER 32P MBE reactor. The growth parameters are presented in Table 1., and are also characterized and described previously [29,30] in terms of the so called mobility spectrum.

The galvano-magnetic measurements were performed in the typical manner at 3–300 K both in the presence of a magnetic field perpendicular to the sample and in the absence of the magnetic field. The samples were shaped as Van der Pauw structures (Figs. 1 and 2) and Hall bar (Fig. 3). The measurements included the Hall concentration n_H vs. temperature, the resistivity in the absence of the magnetic field ρ_0 as a function of temperature, and the Hall mobility vs. temperature at different values of the magnetic field. The electron concentration of the layers was so low that unintentional doping was indicated.

Fig. 1 shows the results of calculations of λ_S vs. temperature and λ_D with Eqs. (2) and (2a) for InAs, in the same results for $In_{0.57}Ga_{0.47}As$ are shown in Fig. 2 and for GaAs in Fig. 3. The parameters are defined in Appendix A.

Table 1
Semiconductor parameters

Semiconductor	Substrate	Deposition temp. (°C)	Layer thickness (μm)	FWHM (arcsec)	Donor state Bohr radius a_B (Å)
InAs	GaAs (0 0 1)	506	9.05	~124	367
$In_{0.57}Ga_{0.47}As$	InP (0 0 1)	510	7	~120	183
GaAs	GaAs (0 0 1)	580	2.3	~28	110