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Low temperature mobility controlled by charged dislocations and neutral defects in $Pb_{1-x}Eu_xSe$ layers grown by MBE

A. Almaggoussi [a,*], A. Abounadi [a], A. Rajira [a], F. Terki [b], S. Charar [b]

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ABSTRACT

Electrical properties of $Pb_{1-x}Eu_xSe$ thin films grown by MBE on two different substrates with varying concentrations of Eu were studied. The electrical measurements were made in the temperature range of 4–300 K. The samples deposited on Si substrate (111) using CaF_2 buffer layer are n-type. Those directly deposited on BaF_2 substrate (111) are all p-type. For europium compositions less than 4%, acoustic phonons, polar optical phonons and neutral impurities mechanisms scattering govern the temperature variations of Hall mobility. Beyond this value of the europium composition, and at low temperature, scattering by charged dislocations becomes the most dominant mechanism.

1. Introduction

The lead salt semiconductors have regained much attention over the past 20 years. This is because of the advanced epitaxial growth techniques applied for the fabrication of IR devices based on the lead salt thin films and their associated quantum heterostructures [1–6]. These materials play an important role as optical sensors covering the wavelength range from 3 µm to over 30 µm. They are also studied as materials for semi-conductor laser diodes operating in the mid-infrared (MIR) range [7]. The growth of IV–VI compounds on Si (111) substrates with intermediate $(Ca, Ba)F_2$ buffer layer in order to overcome the large lattice and thermal expansion mismatch has been pioneered by Zogg et al. [8,9]. Most of the research carried out on these materials has concentrated on growth, structural, magneto-optical and the electrical properties [3–11]. Many calculations and data were published concerning their mobility carriers. The most scattering mechanisms considered are, acoustic phonon, polar optical phonon, ionized impurity and carriers–carriers ones. Whereas, few studies of mobility in the related ternary compounds, particularly PbEuSe, have been made. Investigation of resistivity and Hall concentration of $Pb_{1-x}Eu_xSe$ alloys grown by MBE has been reported earlier [12,13]. The present work is focused on the europium concentration effect on the scattering mechanism in these compounds. At low temperature range, the neutral impurity and the charged dislocations scattering were found to play an important role in the carrier's mobility.

2. Experimental

The samples used in this study were grown by molecular beam epitaxy (MBE) in optimal conditions described elsewhere [12,13]. Two families of samples are subject to study. The first one is constituted by $Pb_{1-x}Eu_xSe$ layers deposited on Si (111) substrate and using CaF_2 buffer layer to control the first stage of nucleation. The europium composition is ranging between 0% and 8% and all the samples are n-type. In the second family, the $Pb_{1-x}Eu_xSe$ layers ($0\% < x < 5\%$) are directly deposited on BaF_2 (111) substrate and the samples are p-type. The Eu concentrations have been estimated by the beam flux ratio of PbSe, Se and Eu concentration effusion cells but have been determined using the bandgap dependence on Eu concentration at room temperature for $Pb_{1-x}Eu_x$ Se, established by Lambrecht et al. [7]: $E_g\ (x,\ T = 300\ \text{K}) = 270 + 2700x$ meV.

Electrical resistivity measurements are carried out in the Van-der-Pauw geometry from 4 K to room temperature. Simultaneously, free electron concentration is obtained by temperature dependent Hall Effect method using a magnetic field of 1 T. The Hall mobility, μ_H, is deduced from the previous measurements for each sample at different temperatures. The composition of Eu checked by microprobe, the thickness checked by optical

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[a] Groupe d'Etude des Matériaux Optoélectroniques (G.E.M.O.), Université Cadi-Ayyad F.S.T.G., BP 549, 40000 Marrakech, Morocco

[b] Institut Charles Gerhardt, UMR 5253, CNRS-UM Université Montpellier II, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France

[*] Corresponding author. Fax: +212 524 43 31 70.
E-mail addresses: a.almaggoussi@uca.ac.ma, alma_rim@yahoo.fr (A. Almaggoussi).

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Table 1
Structural and electrical parameters of investigated PbEuSe samples at room temperature.

Sample	x (%)	d (μm)	n/p (cm^{-3})	μ ($cm^2/V s$)
9648	0	3	1.7×10^{18} (n)	580
9713	4	0.9	7×10^{18} (n)	202
9629	8	1.6	4×10^{17} (n)	41
9703	0	2.09	6.9×10^{17} (p)	244
9710	1.7	3.6	8.5×10^{17} (p)	93
9715	4.8	3.3	1.5×10^{17} (p)	226

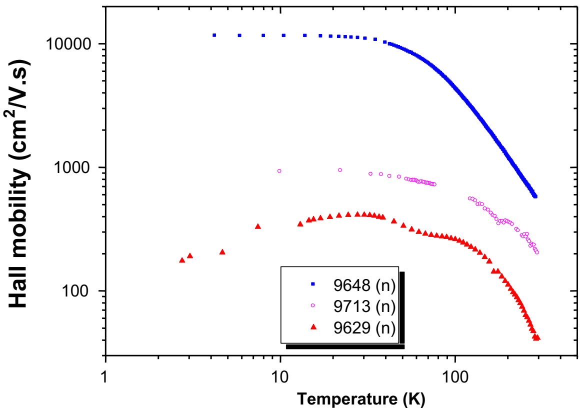

Fig. 1. Log–Log plot for experimental Hall mobility versus temperature for n type samples.

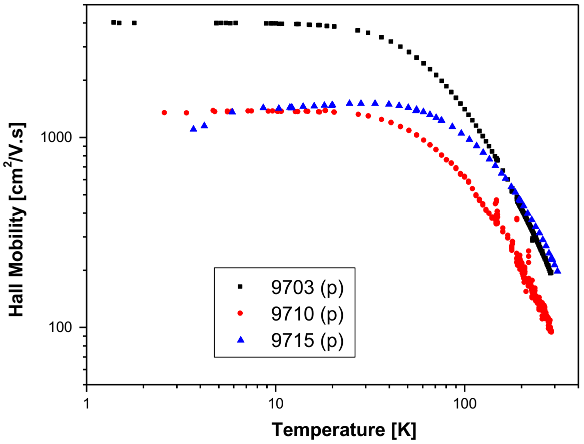

Fig. 2. Log–Log plot for experimental Hall mobility versus temperature for p type samples.

measurements and the electrical parameters of studied samples at room temperature are listed in Table 1. The temperature variations of μ_H plotted in log–log scale are shown in Fig. 1 for n type samples and in Fig. 2 for p type ones.

3. Theoretical approach

Before analyzing our experimental results, let us discuss the relative importance of the various possible scattering mechanisms in the lead salt. The contribution to the mobility in these materials has been studied in greatest detail [14–18] using the relaxation time approximation in order to estimate the strength of the acoustic phonon, ionized impurity and optical phonon scattering.

It is known that the ternary $Pb_{1-x}Eu_xSe$ is subject to an important strain leading to high concentrations of native defects. Thus, one has to consider their related scattering mechanisms in the mobility.

In the following, we give the mobility expression which is employed for each mechanism contribution.

The mobility due to ionized impurities is given, according to the Conwell–Weisskopf formula [19], by:

$$\mu_{C-W}(\mathrm{cm^2/V\,s}) = \frac{64\cdot\pi^{1/2}\,\varepsilon^2(2kT)^{3/2}}{N_I Z^2 e^3 m_e^{1/2}}\left[\mathrm{Ln}\left\{1+\left(\frac{12\pi\,\varepsilon\,kT}{Ze^2N_I^{1/3}}\right)^2\right\}\right]^{-1} \tag{1}$$

where N_I is the density of ionized impurities, Z is the elementary electronic charge and ε is the low frequency dielectric constant.

For the acoustic mode scattering, the mobility is given by [20]:

$$\mu_{ac}\,(\mathrm{cm^2/V\,s}) \quad = \quad 3.\,06\cdot10^4\frac{C_l/10^{12}\quad \mathrm{dyn}\quad \mathrm{cm^{-2}}}{(m/m_0)^{5/2}(T/100)^{3/2}E_{ac}^2} \tag{2}$$

where C_l is the longitudinal elastic constant related to the averaged velocity of sound and E_{ac} is the deformation potential constant.

For optical modes in lead salt, only the polar phonon component is considered. The non-polar optical phonon component is usually neglected because of symmetry considerations [15–17,21]. The polar optical mobility expression is written as [22]:

$$\mu_{po} = \frac{2e}{3\pi^{3/2}\alpha m_e v_e}f(z) \tag{3}$$

$$f(z) = G(z)\cdot\left[e^z - 1\right]\cdot z^{-1/2} \quad z = \frac{h\nu_e}{kT} \tag{4}$$

where $G(z)$ is a tabulated function approximated in the range of 50–300 K by $0.711 + (78\Theta/T^{2.5})$, α is a coupling constant and ν_e is the longitudinal optical mode frequency.

For neutral impurity scattering, the expression used is [23]:

$$\mu_n\left(\mathrm{cm^2/V\,s}\right) = \frac{1.\,44\cdot10^{20}m/m_0}{N_n\varepsilon} \tag{5}$$

where N_n is the density of neutral impurity given in cm^{-3}.

The carriers scattering at charged dislocations lines can have relatively large effect in reducing mobility, particularly at low temperatures. The mobility due to such mechanism is given by the expression [24]:

$$\mu_{disl} = \frac{30\sqrt{2\pi}\,\varepsilon^2\varepsilon_0^2 d^2}{e^2 f^2 L_D m^{1/2}}\frac{(kT)^{3/2}}{N_{disl}} \tag{6}$$

where d is the distance between imperfection centers along the dislocation line, f is their occupation probability, N_{disl} is the density of dislocations and L_D is the Debye screening length.

The temperature variations of the mobility due to each scattering mechanisms for typical PbEuSe sample including 10^{15} cm^{-3} neutral impurities and 10^{17} cm^{-3} ionized impurities are plotted in Fig. 3. The calculations were made using parameters given in Table 2.

4. Results and discussion

The values of mobility deduced from Hall measurements are plotted on a log–log scale in Figs. 1 and 2. At low temperatures ($T < 50$ K), the mobility reaches the values of $1\cdot10^4$ $cm^2/V s$ and $4\cdot10^3$ $cm^2/V s$ for n-type and p-type respectively and decreases drastically when the europium is introduced. This drop attains two orders of magnitude in the silicon substrate case. In this range of