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EFFECT OF CROSSED ELECTRIC AND QUANTIZING MAGNETIC FIELDS ON THE THERMOELECTRIC POWER IN SEMICONDUCTOR SUPERLATTICES

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We study the thermoelectric power of electrons in semiconductor superlattices under cross field configuration and compare the same with the constituent materials, taking $Ga_{1-x}Al_xAs/AlAs$ superlattice as an example. It is found that the thermopower in superlattices increased and the oscillations manifest themselves more significantly when compared to the case of forming compounds.

I. INTRODUCTION

In recent years, with the advent of MBE, MOCVD, FLL and other fabrication techniques, the realization of semiconductor superlattices (SLs) has been possible [1]. The SL, as originally proposed by Esaki and Tsu [1], has found wide applications in many new device structures, such as photodiode photodetectors, transistors, light emitters, electrooptic modulators and other devices [2]. Though extensive work has already been done to study the various electronic properties of such semiconductor heterostructures, it appears that the thermoelectric power (TPM) of SLs has relatively been less investigated [3]. The discovery of quantum Hall effect [4] has brought interest to the study of TPM which has been investigated under different physical conditions [5–8]. The TPM gives information about the density-of-states function and the band structure [9]. In this connection we wish to note that the investigations of the electrons in semiconductors in the presence of crossed electric and quantizing magnetic fields offer interesting physical possibilities, both experimental and theoretical ones [1–11]. The cross-field configuration is fundamental for classical and quantum transport in solids [12–13]. In this paper we shall study the doping and magnetic field dependences of the TPM in SL and the corresponding bulk materials in the presence of crossed electric and magnetic fields, taking $Ga_{1-x}Al_xAs/Al\ As$ SL as an example.

II. THEORETICAL BACKGROUND

In the presence of a quantizing magnetic field B along the SL direction and the crossed electric field E_0 along the x-axis, the Hamiltonian H takes the form

$$H = (\hat{p}_x^2/2m^*) + (\hat{p}_y - eB\hat{x})^2/2m^* + E_{os} - E_{is}\cos(2\pi\hat{p}_z/K_0) - eE_0\hat{x}. \quad (1)$$

In eq. (1), the hats denote the respective operators; the other symbols have been defined in [14]. The modified electron energy spectrum for SLs, including spins, reads

$$\varepsilon = (n+\frac{1}{2})\hbar\omega_0 - eE_0p_y/m^*\omega_0 - e^2E_0^2/2m^*\omega_0^2 + E_{os} - \\ - E_{is}\cos(2\pi k_z/K_0) \pm \frac{1}{2}\cdot g_0\mu_0 B, \quad (2)$$

where ε is the electron energy in the presence of cross field configuration which is measured from the band gap of the material, where this energy band gap in the absence of the cross-field configuration is smaller. n $(0, 1, 2, \ldots)$ is the Landau quantum number, $\omega_0 = eB/m^*$, g_0 is magnitude of the band-edge g factor and μ_0 is the Bohr magneton. We consider only the lowest miniband, since only this one is significantly populated in actual SI at low temperatures where the quantum effects become prominent. The electron statistics can be expressed, including both spin and broadening effects, as

$$n_0 = c_0\sum_{n=0}^{n_{max}}[p(E_F) + Q(E_F)], \quad (3)$$

where $c_0 = (n^*w_0\ E_{is}/2eE_0\hbar\pi^2d_0^2)$, d_0 is the SL period,

$$p(E_F) = \mathrm{Re}\,[\{1-(a_1-b_1x_1)^2\}^{1/2} - (a_1-b_1x_1)\cos^{-1}\{(a_1-b_1x_1)\} - \\ - \{1-(a_1-b_1x_2)^2\}^{1/2} + (a_1-b_1x_2)\cos^{-1}\{(a_1-b_1x_1)\}],$$

$$a_1 = (E_{is})^{-1}[E_{os} + \left(n+\frac{1}{2}\right)\hbar\omega_0 - (e^2E_0^2/2m^*\omega_0^2) - E_F - i\Gamma],$$

E_F is the Fermi energy, $\Gamma(\pi k_BT_D)$ is the broadening parameter [15], T_D is the Dingle temperature, $x_1 = eBd_0/\hbar + x_2$, $x_2 = -m^*E/(2Bh)$, $Q(E_F) = \sum_{r=1}^{t}\nabla_r\,[P\,(E_F)]$, $\nabla_r = 2(k_BT)^{2r}(1-2^{1-2r})\zeta(2r)\,\mathrm{d}^{2r}/\mathrm{d}E_F^{2r}$, r is the set of real positive integers, k_B is the Boltzmann constant, T is temperature and $\zeta(2r)$

is the zeta function of order $2r$ [16]. The TPM in the present case can be written as [9]

$$G = L/en_0, \tag{4}$$

where L is the corresponding entropy per unit volume. Thus combining (3) and (4), we get

$$G = (\pi^2 k_B^2 T c_0/3en_0) \sum_{n=0}^{n_{max}} [P'(E_F) + Q'(E_F)], \tag{5}$$

where the primes denote the differentiation with respect to E_F. We shall now derive the expressions for n_0 and TPM in those bulk materials that have parabolic energy bands. This will be done for the purpose of comparison under cross-field configuration. The dispersion relation for the said system can be written [13] as

$$\varepsilon = \left(n + \frac{1}{2}\right)\hbar\omega_0 - \frac{eE_0 p_y}{m^*\omega_0} + \frac{p_z^2}{2m^*} - \frac{e^2E_0^2}{2m^*\omega_0^2} \pm \frac{1}{2}(g_0\mu_0 B). \tag{6}$$

The expressions of n_0 and TPM can be written using (6) as

$$n_0 = C_1 \sum_{n=0}^{n_{max}} [\alpha(n, E_{FB}) + \beta(n, E_{FB})] \tag{7}$$

and

$$G = (\pi^2 k_B^2 T C_1/3en_0) \sum_{n=0}^{n_{max}} [\alpha'(n, E_{FB}) + \beta'(n, E_{FB})], \tag{8}$$

where the notations are defined in [12].

III. RESULTS AND DISCUSSION

Using (3) and (5) together with the material parameters [17, 20] $m^* = (0.067 + 0.083x)\, m_0$, $x = 0.2$, $d_0 = 8$ nm, $E_{01} = 0.05$ eV, $B = 2$ Tesla, $E_{11} = 0.01$ eV, and $E_0 = 10^3$ V/m for $Ga_{1-x}Al_xAs/AlAs$ SL, we have plotted the normalized TPM versus n_0 as shown in plot a of Fig. 1. in which the curves of band C exhibit according to (7) and (8) the same dependence for GaAs ($m^* = 0.067\, m_0$) and AlAs ($m^* = 0.150\, m_0$), respectively. The curves d, e and f exhibit the same dependence in the absence of electric field. Taking the same parameters as used in Fig. 1, we have also plotted the normalized TPM's as functions of quantizing magnetic field in all the aforementioned cases of Fig. 1 corresponding to an electron concentration of 10^{23} m^{-3}.

It is seen from Fig. 1 that the TPM increases with decreasing electron concentration in an oscillatory manner. The presence of electric field enhances the values of the TPM as seen by comparing the plots a and d of Fig. 1 in the whole range of the concentrations considered here. Fig. 2 shows that the TPM in the SLs and the constituent materials oscillates with increasing B. The origin of the oscillations of

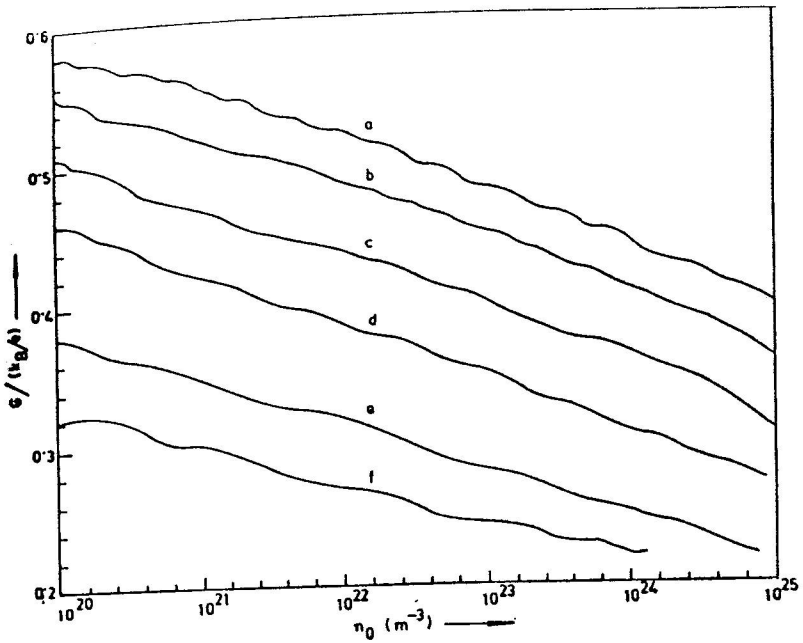

Fig. 1. Plot of the normalized TPM under cross-field configuration versus n_0 in (a) $Ga_{1-x}Al_xAs/AlAs$ SL; (b) GaAs and (c) AlAs. The plots, d, e and f correspond to $E_0 = 0$.

the TPM is the same as that of the Shubnikov - de Hass oscillations. For extremely large value of the quantizing magnetic field, the conditions of the quantum limit will be reached when the TPM will be found to increase monotonically with increasing magnetic field. The highest values of the TPM are for SL structure under cross-field configuration, whereas the least ones are for AlAs. As seen from both Figures, the oscillations are totally band structure dependent.

Incidentally, though we are not aware of any availanle experimental data related to our results the expressions given here would be useful in analysing of the experimental datas when they will be measured. The experimental value of the TPM under cross field configuration will provide an experimental check on the thermopower and also a technique for probing the band structures. The TPM could be plotted also with respect to other physical variables. We have numerically evaluated several cases for the purpose of condensed presentation. For the sake of simplicity we have neglected the band nonparabolicity. We get the different numerical values of the TPM with different sets of energy band constants, though the nature of variations will not be altered. The basic aim of our present paper is not solely to demonstrate the effect of cross-field configuration on the TPM of the SLs and the constituent materials, but also to derive the expression of the electron concentration in the respective cases, because the formulations of the various

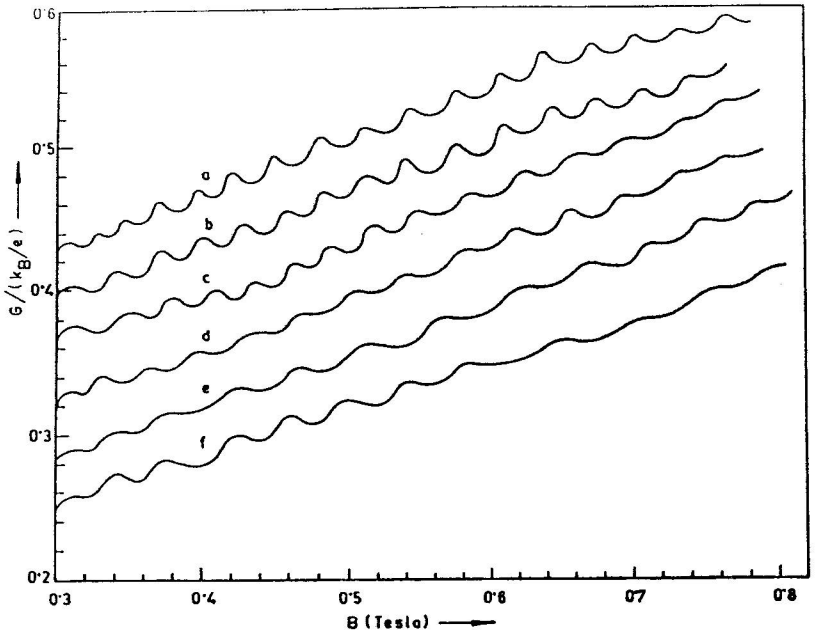

Fig. 2. Plot of the normalized TPM under cross-field configuration versus B for all the cases of Fig. 1.

transport coefficients depend on the electron statistics in such materials. Finally, it may be noted that the conclusions made here would be of particular significance in view of the fact that the Einstein relation for the diffusivity-mobility ratio and the carrier contribution to the elastic constants in materials with arbitrary band structure can be related to the TPM [18, 19].

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