

Computation of the Effective Hall Factor of p-GaSb

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Abstract: The effective Hall factor (γ_{eff}) of p-type GaSb semiconductor was investigated using the two-band model assuming parabolic valence bands. The calculations were based on the relaxation time approximation taking into account lattice and impurity scattering effects as a function of the temperature. Some transport parameters of p-GaSb were determined by assuming that the bands of heavy and light holes are decoupled. The mobility ratio between the deformation potential and ionized impurity scattering decreased with elevation of temperature. If the impurity scattering exceeds all other scattering processes, the approximation of $\gamma_{eff} \sim 1$ is valid. On the other hand if the lattice scattering process dominates, the approximation of $\gamma_{eff} \sim 1$ is not valid. The temperature dependence of the effective Hall factor was studied. The results showed that the effective Hall factor decreased with decreasing the temperature.

Key words: effective Hall factor, lattice scattering, ionized impurity scattering, hole mobility.

INTRODUCTION

Carrier transport measurements continue to be a valuable means for characterizing semiconductor materials. Improvements in transport calculations, especially for *n*-type materials, have contributed greatly to elucidating particle scattering mechanisms, as well as to refining our knowledge of basic material constants (Nag, B.R., 1980; Look, D.C., 1989; Szymd, D.M., 1990). For *p*-type semiconductors, the presence of the coupled heavy-hole and light-hole bands (the third split-off band is ignored provided that it is sufficiently separated from the two valence bands) introduces considerable complexity into transport calculations. It has been recognized that both intraband and interband scattering processes are important (Brudevoll, T., 1990) and contribute significantly to the transport of charge carriers (Wiley, J.D., 1975), and also that in general anisotropy and nonparabolicity of the valence-band structure result in a considerable effect on the total scattering rates, with different magnitude for various scattering mechanisms (Lawaetz, P., 1968).

A full consideration of the complexity of the valence band structure and its influence on the transition rates render an analytical treatment impossible, and numerical techniques must then be applied. The standard way of handling the transport problem in the interacting two-band model is first to set up and then solve the coupled Boltzmann equations. Although this can be carried out in principle by procedures such as the variational (Kohler, M., 1949; Howarth, D.J. and E.H. Sondheimer, 1953), iterative (Rode, D.L., 1970; Takeda, K., 1985), Monte Carlo techniques (Hinckley, J.M. and J. Singh, 1994; Brennan, K. and K. Hess, 1984) and others (Lawaetz, P., 1968; Szmulowicz, F., 1986), these methods could carry the disadvantages of intensive computational work and reduced physical insight into the problem.

In order to simplify the problem of solving the Boltzmann equation and provide a useful general understanding of the physics, several methods have been proposed based on the relaxation time (RT) concept in the isotropic band approximation. The simplest model in this approach assumes that the two bands are completely decoupled (Wiley, J.D., 1971). Although this decoupled approximation has been used in many cases (Walukiewicz, W., 1982; Walukiewicz, W., 1990), it has proved to be extremely poor in the case of phonon scattering. In order to include the presence of interband scattering, a more rigorous formula was presented (Bernard, W., 1963) and later, as a simplified version of this formula, a "partial coupling approximation" was proposed (Wiley, J.D., 1975).

Transport calculations have been performed for *p*-type materials by treating the heavy-and light-hole bands as a single heavy-hole band, incorporating corrections to compensate for some possible deficiencies in this treatment (Lowney, J.R. and H.S. Bennett, 1991). Although transport calculations based on such approximation

have shown good agreement with experimental results, this approximation may not provide an adequate quantitative physical picture of the processes involved in two-band transport, such as the Hall factor, the contributions of each type of particle to the total mobility, and the importance of various interband scattering mechanisms. In order to obtain this information, it is necessary that the interactions between the two bands be explicitly taken into account in theoretical calculations.

In this work, the effective Hall factor of p-type Gallium Antimonide (GaSb) semiconductor is investigated theoretically using the two band model. Mobilities were calculated using the relaxation time approximation (Alfaramawi, K. and M.A. Alzamil, 2009). GaSb and its alloys and heterostructures are promising materials for optoelectronics and other semiconductor devices in the near infrared spectra. More researches are required to understand and investigate the effect of defects and impurities on the electrical and transport properties of GaSb. Intentionally, GaSb is p-type with excess hole concentrations of about 10^{16} - 10^{17} cm⁻³ due to residual acceptor that is related to Ga excess atom. This acceptor has been associated to the $V_{Ga}Ga_{Sb}$ complex (Podor, B., 2005).

2. Theory:

In n-type semiconductors there are no significant differences between the free electron concentration n and the electron drift mobility μ and the corresponding electrically measured values (Hall concentration n_H and the Hall mobility μ_H) (Wenzel, M., 1998).

In p-type semiconductors with two carrier types (heavy and light holes) the Hall concentration p_H and the Hall mobility differ from the free hole concentration p and the drift mobility μ by the effective Hall factor r_{eff} (Wenzel, M., 1997), where

$$p = r_{eff} p_H \quad (1)$$

$$\mu_H = r_{eff} \mu \quad (2)$$

The Hall factor for heavy holes is denoted by r_1 while for the light holes is r_2 . Using the relaxation time approximation, the effective Hall factor is given by (Irmer, G., 1991)

$$r_{eff} = \frac{(1 + \alpha^{3/2})(r_1 \alpha^{3/2} \beta^2 + r_2)}{(1 + \alpha^{3/2} \beta)^2} \quad (3)$$

where

$$\alpha = \frac{m_1}{m_2} \quad \text{and} \quad \beta = \frac{\mu_1}{\mu_2} \quad (4)$$

m is the effective mass. The index 1 always refers to heavy and the index 2 to light holes. In a first approximation, we assume that the bands of heavy and light holes are decoupled and that $r_1 = r_2 = 1$ (Wiley, J.D. and M.D. Domenico, 1970; Somogyi, K., 1976). Hence

$$r_{eff} = \frac{(1 + \alpha^{3/2})(\alpha^{3/2} \beta^2 + 1)}{(1 + \alpha^{3/2} \beta)^2} \quad (5)$$

From this equation one can conclude that the effective Hall factor is well specified by the function β . The mobility ratio β depends on scattering mechanisms. In this case, β reduces to a simple power of α . In the case of deformation potential scattering by optical and acoustic phonons, the mobility ratio is defined as

$$\beta_D = \frac{\mu_{1D}}{\mu_{2D}} = \alpha^{-1}$$

For polar optical phonon scattering we have

$$\beta_P = \frac{\mu_{1P}}{\mu_{2P}} = \alpha^{-3/2}$$

and for scattering by ionized impurities

$$\beta_I = \frac{\mu_{1I}}{\mu_{2I}} = \alpha^{-1/2}$$

The scattering mechanisms are mixed in a real sample and, therefore the resulting effective Hall factor may be expected to be dependent on the relative contributions of the scattering mechanisms. The resultant value of β due to the mix of scattering processes can be obtained by using Mathiessen's rule

$$\frac{1}{\beta} = \frac{1}{\beta_D} + \frac{1}{\beta_P} + \frac{1}{\beta_I} \quad (6)$$

Hence we can get

$$\beta = \frac{\alpha^{1/2} + \alpha \delta + \theta}{\alpha^{3/2}(1 + \delta + \theta)} \quad (7)$$

where

$$\delta = \frac{\mu_{1D}}{\mu_{1I}} \quad \text{and} \quad \theta = \frac{\mu_{1D}}{\mu_{1P}} \quad (8)$$

The problem then is transformed to a single type carrier scattering. The parameter θ is influenced only by lattice scattering processes and depends on temperature. The parameter δ depends on the ionized impurity scattering and subsequently on the acceptor concentration. In the case of high purity samples, scattering by ionized impurities is negligible at room temperature. Generally, the effective Hall factor in semiconductors depends strongly on the temperature.

RESULTS AND DISCUSSION

Calculations of the effective Hall factor and some transport parameters were carried out in a temperature range from 10 K up to 300 K. The physical constants used in the calculations are listed in table 1.

The dominant scattering centers in this range of temperature are mainly the ionized impurities and the lattice acoustic phonon scattering. Fig. 1 shows the calculated hole mobility as a function of temperature for p-GaSb including the ionized impurity scattering and the acoustic phonon scattering with the two types, deformation potential and piezoelectric acoustic phonons. The calculations were performed at acceptor concentration of $7.5 \times 10^{20} \text{ m}^{-3}$.

It was reported by Alfaramawi (2010) and Alfaramawi and Alzamil (2009) that the piezoelectric acoustic phonon scattering can be ignored with respect to the effect of the deformation potential acoustic phonon scattering. Therefore, the mobility curve due to the acoustic phonon scattering can be considered to represent the deformation potential branch of the acoustic phonon scattering.

In Fig. 2, the function δ , which represents the mobility ratio between deformation potential scattering to the ionized impurity scattering (see equation 8), was plotted against the temperature at different values of the acceptor concentrations. It was noticed that the mobility ratio decreases with elevation of temperature and this is probably attributed to the effect of ionized impurity scattering particularly at low temperatures.

Table 1: Some physical constants of p-type GaSb

Parameter	Value	Reference
Static dielectric constant (ϵ)	15.7	(Jain, S.L., 1990)
High frequency dielectric constant (ϵ_∞)	14.4	(Jain, S.L., 1990)
Heavy hole effective mass (m_h^*)	0.4 m_0	(Heller, M.W. and R.G. Hamerly, 1985)
Light hole effective mass (m_l^*)	0.05 m_0	(Heller, M.W. and R.G. Hamerly, 1985)
Mass density (ρ)	$5.61 \times 10^3 \text{ Kg}$	(Johnson, G.R., 1988)
Deformation potential (E_i)	3.6 eV	(Podor, B., 2005)
Debye temperature (T_D)	266 K	(Podor, B., 2005)

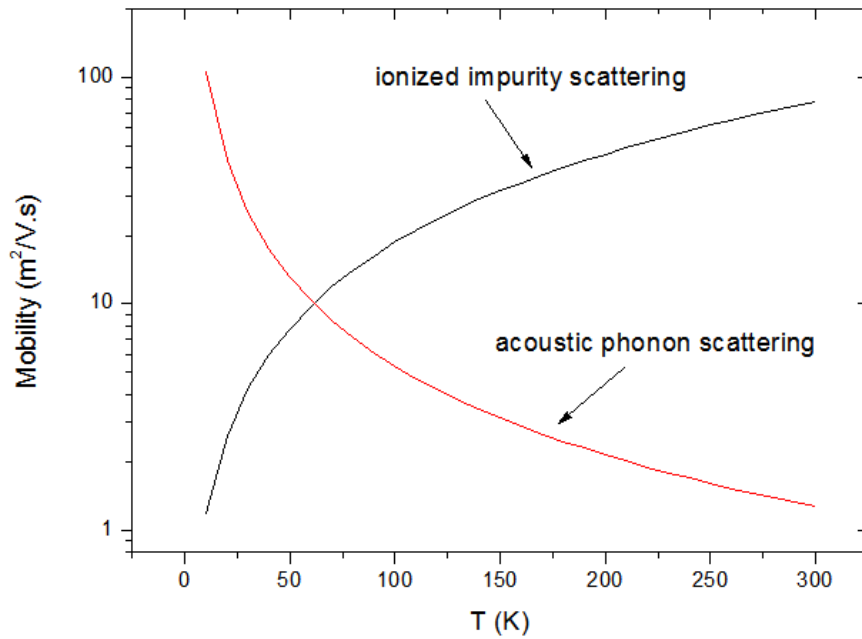


Fig. 1: Calculated hole mobility as a function of temperature of p-GaSb

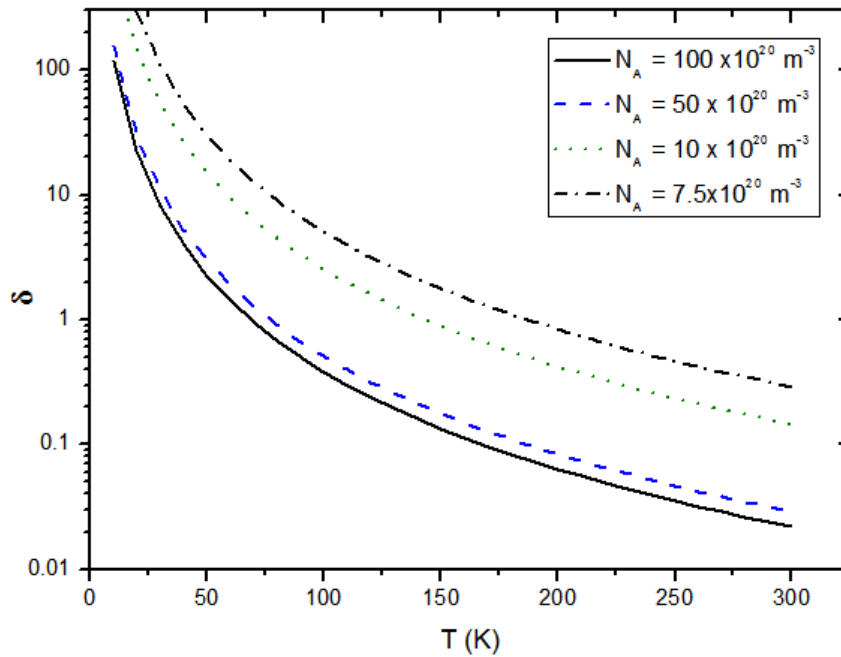


Fig. 2: The mobility ratio between deformation potential scattering to the ionized impurity scattering against the temperature at different values of the acceptor concentrations

As mentioned before, the effective Hall factor is specified by determining the function β which itself depends on the parameters δ and θ . Fig. 3 represents the dependence of the function β on the parameter δ at two values of the parameter θ . Inspection of Fig. 3 reveals that the curves tend to take nearly finite values at both high and low values of the mobility ratio δ and the finite value of β at high mobility ratio is about 0.35 independent on the parameter θ i.e. on the lattice scattering.

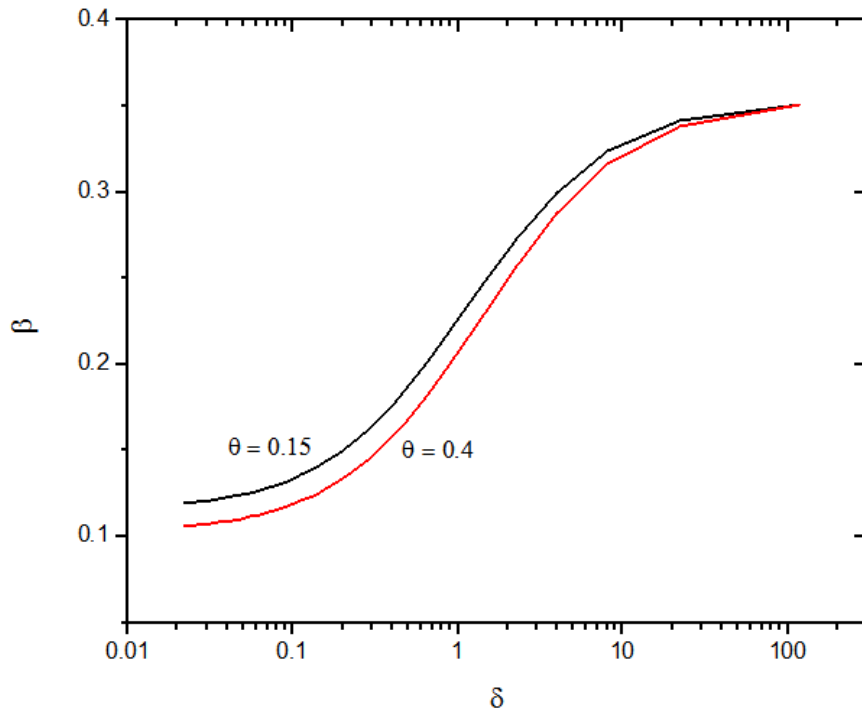


Fig. 3: The dependence of the function β on the parameter δ at two values of the parameter θ

On the other hand, the dependence of the function β on the temperature was demonstrated in Fig. 4. The function decreases monotonically by increasing the temperatures and tends to a finite value at high temperatures.

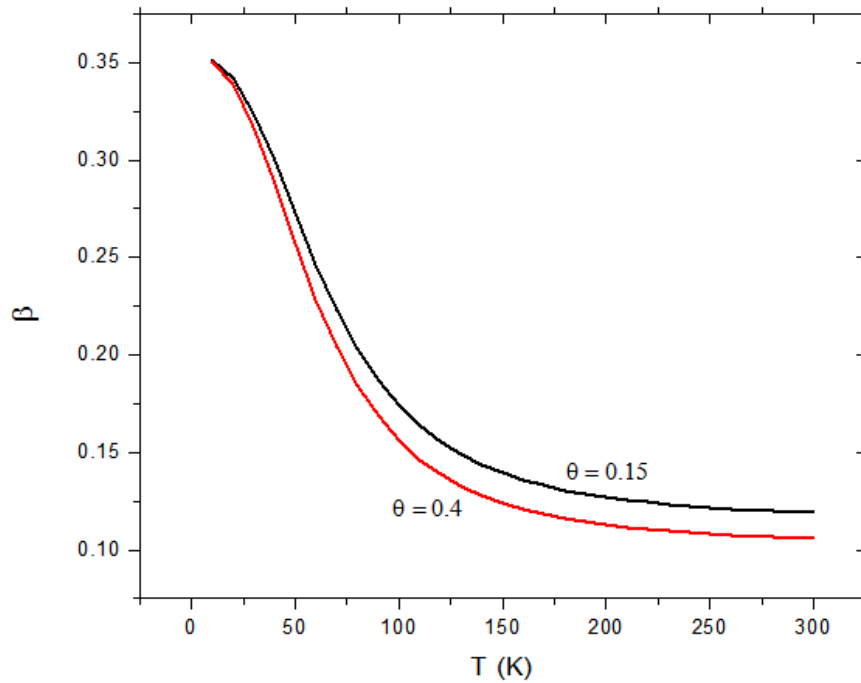


Fig. 4: The dependence of the function β on the temperature

A significant influence of the effective Hall factor on the evaluation of the optical and electrical determination of the hole concentration can be expected rather for pure samples with a small contribution of ionized impurity scattering.

The effective Hall factor obtained from equation (5) with equation (7) depends for a given θ on the parameter δ . Increasing the parameter δ means the possible decrease of the mobility (μ_i) and this indeed refers to the great influence of the scattering by ionized impurities. Fig. 5 displays the dependence of the effective Hall factor on the temperature at two values of θ for p-GaSb. With increasing δ , i.e. with increasing influence of scattering by ionized impurities, the effective Hall factor decreases. At large values of δ , the impurity scattering exceeds all other scattering processes and accordingly the approximation of $\gamma_{eff} \sim 1$ is nearly valid. On the other hand, at small values of δ , the lattice scattering process dominates and the approximation of $\gamma_{eff} \sim 1$ is not valid and its value varies between 2.3 and 2.6 at the selected values of θ .

The temperature dependence of the effective Hall factor is determined only by considering the lattice scattering mechanism. In order to neglect the effect of the ionized impurities in the scattering processes, calculations were performed at the case of low carrier concentration. Fig. 6 shows the temperature dependence of the effective Hall factor.

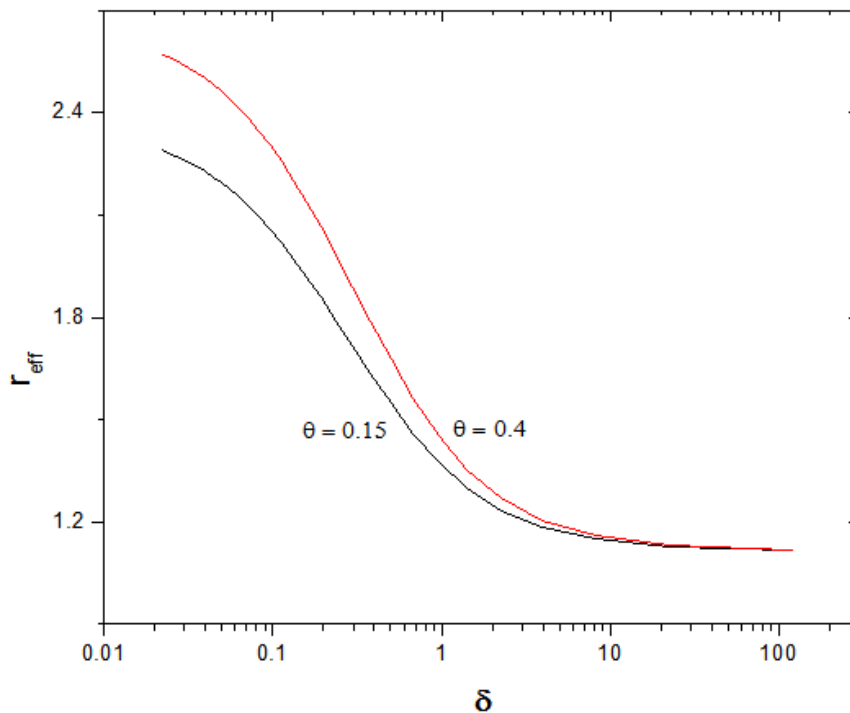


Fig. 5: Dependence of the effective Hall factor on the parameter δ at two values of θ .

From the figure one can notice that the effective Hall factor decreases with decreasing the temperature. At low temperature range, when the influence of the lattice scattering becomes negligibly small, the effective Hall factor may approach to unity. At high temperatures the lattice scattering become more effective and this leads to increase the value of the effective Hall factor.

4. Conclusions:

Calculations of the effective Hall factor and some transport parameters were carried out in a temperature range from 10 K up to 300 K. The dominant scattering centers in this range of temperature were mainly the ionized impurities and the lattice acoustic phonon scattering. The mobility ratio between deformation potential scattering to the ionized impurity scattering (δ) decreased with elevation of temperature and this was probably attributed to the effect of ionized impurity scattering particularly at low temperatures. The effective Hall factor was studied as a function of the parameter δ . With increasing δ , i.e. with increasing influence of scattering by ionized impurities, the effective Hall factor decreased. If the impurity scattering mechanism dominates, the effective Hall factor may approach the unity. On the other hand when the lattice scattering process dominates,

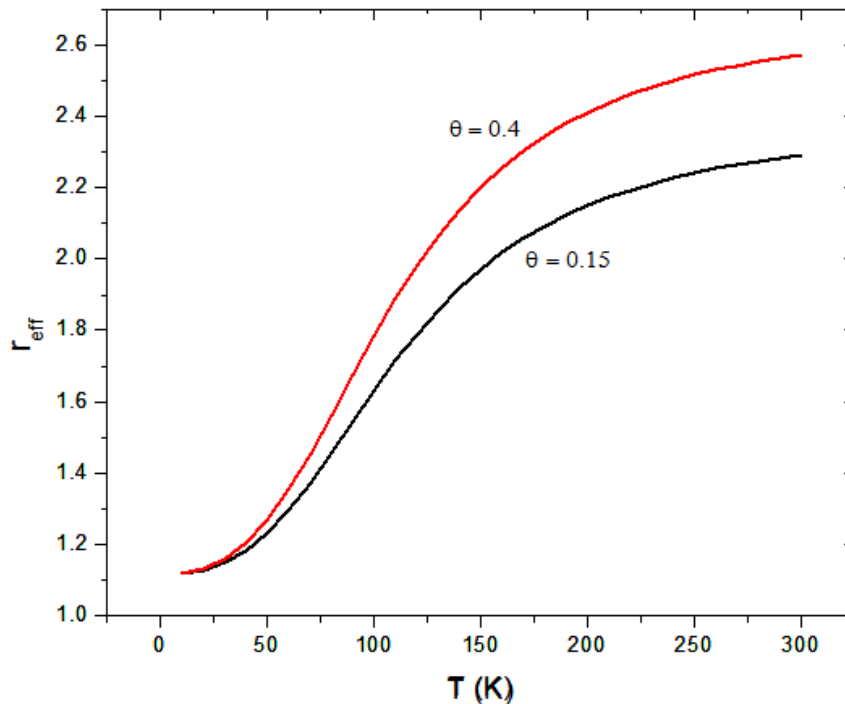


Fig. 6: The temperature dependence of the effective Hall factor

this approximation was not valid. In this case the effective Hall factor varied between 2.3 and 2.6. The temperature dependence of the effective Hall factor was studied only by considering the lattice scattering mechanism in the case of low carrier concentration. It was found that the effective Hall factor decreased with decreasing the temperature. At low temperature range, the effective Hall factor may approach to unity

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REFERENCES

- Alfaramawi, K., 2010. Optoelectron. Adv. Mat. Rapid Communications, 4: 922.
- Alfaramawi, K. and M.A. Alzamil, 2009. Optoelectron. Adv. Mat. - Rapid Communications, 3: 569.
- Brudevoll, T., T.A. Fjeldly, J. Baek and M.S. Shur, 1990. J. Appl. Phys., 67: 7373.
- Brennan, K. and K. Hess, 1984. Phys. Rev., B 29: 5581.
- Bernard, W., H. Roth and W.D. Straub, 1963. Phys. Rev., 132: 33.
- Howarth, D.J. and E.H. Sondheimer, 1953. Proc. R. Soc. London Ser., A 219: 53.
- Hinckley, J.M. and J. Singh, 1994. J. Appl. Phys., 76: 4192.
- Heller, M.W. and R.G. Hamerly, 1985. J. Appl. Phys., 57: 4626.
- Irmer, G., W. Siegel, G. Kuhnel, J. Monecke, F.M.M. Yasuoka, B.H. Bairamov and V.V. Toporov, 1991. Semicond. Sci. Technol., 6: 1072.
- Jain, S.L., J.M. McGregor and D.J. Roulston, 1990. J. Appl. Phys., 68: 3747
- Johnson, G.R., B.C. Cavenett and T.M. Kerr, 1988. Semicond. Sci. Technol., 3: 1157.
- Kohler, M., 1949. Z. Phys., 125: 679.
- Look, D.C., 1989. Electrical Characterization of GaAs Materials and Devices, Wiley, New York.
- Lawaetz, P., 1968. Phys. Rev., 166: 763.
- Lawaetz, P., 1968. Phys. Rev., 166: 763.
- Lowney, J.R. and H.S. Bennett, 1991. J. Appl. Phys., 69: 7102.
- Nag, B.R., 1980. Electron Transport in Compound Semiconductors, Springer, Berlin.

- Podor, B., 2005. *Acta Phys. Pol.*, 108: 837.
- Rode, D.L., 1970. *Phys. Rev.*, 2: 1012.
- Somogyi, K., 1976. *Phys. Status Solidi, A* 37: 653.
- Szmyd, D.M., M.C. Hanna and A. Majerfeld, 1990. *J. Appl. Phys.*, 68: 2376.
- Szmulowicz, F., 1986. *Phys. Rev.*, B 34: 4031.
- Takeda, K., N. Matsumoto, A. Taguchi, H. Taki, E. Ohta and M. Sakata, 1985. *Phys. Rev.*, B 32: 1101.
- Wiley, J.D., 1975. *Mobility of Holes in III–V Compounds*, in *Semiconductors and Semimetals*, Academic, New York, 10: 1-89.
- Wiley, J.D., 1971. *Phys. Rev.*, B 4: 2485.
- Walukiewicz, W., L. Pawlowicz, J. Lagowski and H.C. Gatos, 1982. *Proceedings of the Conference on Semi-Insulating III–V Materials*, Evian, 1982, edited by Ebeid S. M. and Tuck B., Shiva Nantwich, UK, pp: 121.
- Walukiewicz, W., 1990. *Phys. Rev.*, B41: 10218.
- Wenzel, M., G. Irmer, J. Monecke and W. Siegel, 1998. *Semicond. Sci. Technol.*, 13: 505.
- Wenzel, M., G. Irmer, J. Monecke and W. Siegel, 1997. *J. Appl. Phys.*, 81: 7810.
- Wiley, J.D. and M.D. Domenico, 1970. *Phys. Rev.*, B 2: 427.