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PHONON ASSISTED TUNNEL EMISSION OF ELECTRONS FROM THE Cr LEVEL IN GaAs

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The electron emission rate e_n from the Cr deep level in GaAs is found to be strongly electric field dependent. This causes spectacular distortions in the DLTS and ODLTS spectra. The temperature and electric field dependence of e_n is accurately accounted for by a phonon assisted tunnel emission model. A best fit procedure yields a reliable estimate for the Franck-Condon shift $S\hbar\omega$ and a rough estimate for $\hbar\omega$. This is the first time that non optical measurements allow an evaluation of the lattice relaxation parameters S and $\hbar\omega$ for the Cr level.

I. Introduction

Chromium doping of GaAs introduces a deep level near the middle of the band gap. This level manifests itself both as a hole trap and as an electron trap. This is the only level in GaAs known to have this behaviour.

Previous detailed electrical characterization of the Cr level in GaAs has been made by capacitive techniques in low electric field conditions [1]. Under these conditions, the ratio e_n/e_p of the electron to hole emission rate is found to be about 0.7×10^{-2}, meaning that the level acts predominantly as a hole trap. These previous measurements were carried out on slightly doped ($n = 6 \times 10^{14}$ cm^{-3}) liquid phase epitaxial layers. Three other n-type layers doped with Cr, have been grown with free electron concentrations of 0.04, 0.45 and 2×10^{17} cm^{-3} in order to reach moderate and high electric field conditions. LPE layers are more suited to this type of study than VPE layers or bulk material because of the absence of any observable native electron trap and the very small concentration of native hole traps.

II. Experimental Results

Capacitance measurements have been performed on Au Schottky diodes. DLTS (electrical refilling of traps) and ODLTS (optical refilling) spectra are shown in

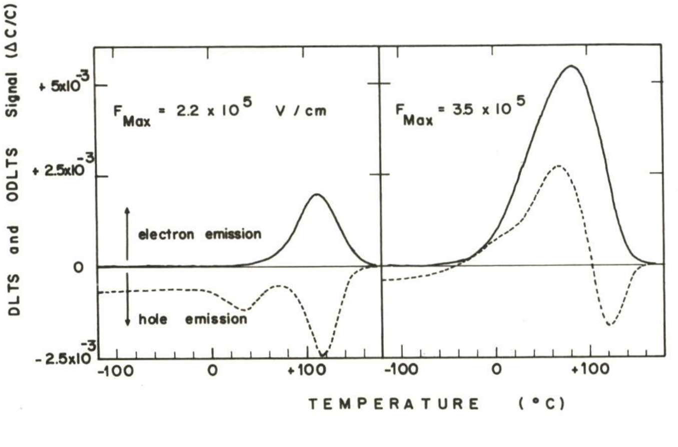
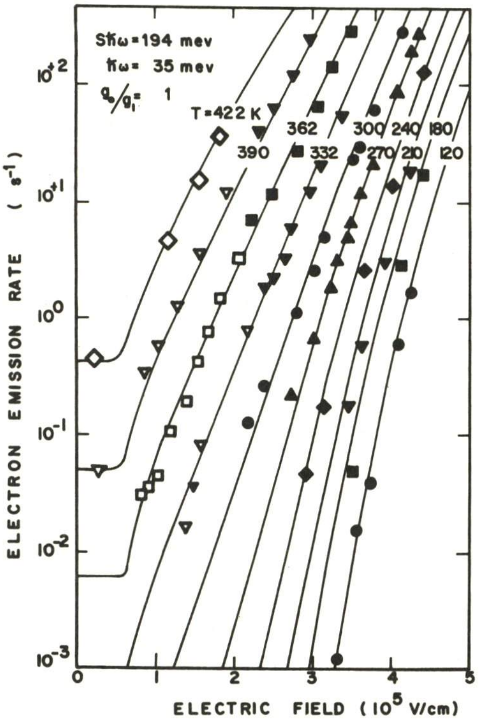


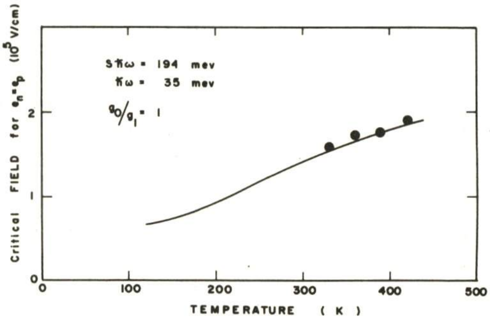
Figure 1 DLTS (solid curves) and ODLTS (broken curves) spectra made under two conditions of electric field: Emission rate window at 0.133 s^{-1}
Free electron density in LPE layer = 4.5×10^{16}cm^{-3}
Reverse bias = 3 V (left) and 8 V (right)

Fig. (1), corresponding respectively to an electron refilling ratio of 1 and 0.85. The Cr level represents the major contribution to these spectra, while the native hole trap HL2 gives rise either to a small peak or to a shoulder near 40°C. The effect of electric field is apparent even in the case of fields $<2.2 \times 10^5$ Vcm^{-1} leading to an important widening of the electron emission peak and to a ratio of electron to hole emission peaks about 8 times larger than for low field conditions [1] . For higher fields ($F_{max} = 3.5 \times 10^5$) the same effects are more pronounced and the electron emission manifests itself even in the ODLTS spectrum, the level becoming an electron trap ($e_n \gg e_p$).

A differential capacitance transient technique [2] has been used to determine the electron emission rate as a function of electric field and temperature. When the electron and hole emission rates e_n and e_p are of comparable magnitude, the time constant of the differential transient is equal to $(e_n + e_p)^{-1}$ and its amplitude proportional to $N_T e_n \times (e_n + e_p)^{-1}$, N_T being the Cr concentration. The value of N_T can deduced from measurements under high field conditions where $e_n \gg e_p$. For other conditions, the above method allow an independent evaluation of e_n and e_p.

The points in Fig. (2) give the measured critical field for which $e_n = e_p$. Figure (3) shows the electric field and temperature dependence of the electron emission rate. The empty points and the solid points correspond respectively to the cases where $e_n \sim e_p$ and $e_n \gg e_p$. The hole emission rates are found to be larger than their low field values by factors ranging from 1.2 to 1.4, even for electric fields as high as 2×10^5 V cm^{-1}, an unsignificant increase as compared to that of e_n.





↑Figure 2 Critical electric field for which $e_n = e_p$ as a function of temperature: The curve corresponds to theoretical calculations with the parameters required for closest fitting the results of Fig. (3)

←Figure 3 Dependence of the electron emission rate e_n on electric field and temperature: The curves correspond to theoretical calculations assuming unity degeneracy ratio g_0/g_1. The values of $S\hbar\omega$ and $\hbar\omega$ taken are those required to achieve the best agreement with the experimental data points

III. Comparison of Experiments with Theory

A phonon assisted tunneling mechanism allows to account for the experimental results. The small effective mass for electrons compared to the hole effective mass explains why e_n is more field dependent than e_p. A semi-classical model has previously been published [3]. A more rigorous version of the model is used here [4].

In this model, the electron level is assumed to be linearly coupled to phonons having a well defined energy $\hbar\omega$ with a Huang-Rhys coupling constant S. Due to this coupling, the trapped electron can occupy a set of stationary quasi-levels separated by $\hbar\omega$. Elastic tunneling can then occur from any one of these levels to the conduction band. The occupation probability of any of these levels is a function of S, $\hbar\omega$ and T. When the temperature and the coupling constant S are high, the electron has a non-negligible probability of occupying quasi-levels near to the conduction band and, as a result, the tunnel emission rate is greatly enhanced by the coupling with phonons. The best fit of experimental data reported in Fig. (3) has yielded the following value of the parameters $S\hbar\omega$ and $\hbar\omega$

$S\hbar\omega = 195 \pm 15$ meV,
$\hbar\omega = 35 \pm 10$ meV.

From optical absorption data, it was previously deduced that $S\hbar\omega = 170$ meV with $\hbar\omega = 28$ meV [5]. The same parameters can also be estimated by trying to account for the temperature dependence of the electron capture cross section σ_n. Figure (4) shows experimental data fitted by different curves calculated after Ridley [6] from the expression

$$\sigma_n = \sigma_0 \, (\bar{n} + 1)^p \cdot e^{-2\bar{n}S}, \qquad (1)$$

where $\bar{n} = \left[\exp(\hbar\omega/kT) - 1\right]^{-1}$, p is the electron free energy of ionisation in units of $\hbar\omega$ and σ_0 is a factor related to the (unknown) very low temperature behaviour of σ_n. One obtains $S\hbar\omega = 180 \pm 25$ meV and $\hbar\omega = 40 \pm 5$ meV.

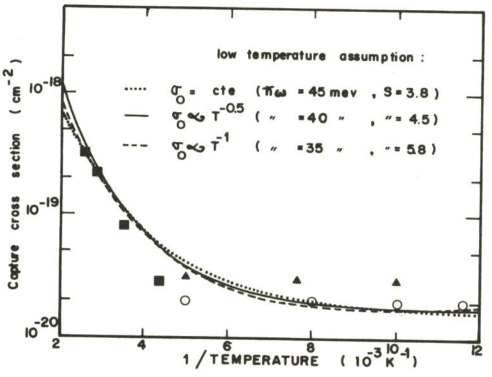


Figure 4 Electron capture cross-section σ_n versus the reciprocal of absolute temperature: The circles are experimental after Jesper et al.[8] , the squares are after Mitonneau et al.[9] and the triangles are experimental points of this work

The above fitting procedure makes use of the low temperature approximation proposed by Ridley (eq. (1)). By applying a test due to this author, we see that the large values of S involved render critical the use of this approximation in the whole temperature range for which the fit is to be realized.

A more reliable and accurate evaluation of $\hbar\omega$ can be obtained by still another method. By making use of the theory of Ridley [6], Burt [7] has noted that an accurate evaluation of S can be deduced from a rough estimation of the magnitude of σ_n at the lowest possible temperature where Ridley approximations hold. Burt uses an expression linking S to σ_n and p. The resulting value of S clearly depend on the choice of $\hbar\omega$ (through p). We apply this method by imposing the condition that the value of $S\hbar\omega$ should fall within a range corresponding to the values deduced in this work from phonon assisted tunneling emission and the value deduced from optical absorption measurements by Hennel et al. [5] , i.e.

$S\hbar\omega = 190 \pm 20$ meV.

This is found to be possible only if $\hbar\omega$ falls within the interval

$$\hbar\omega = 27 \pm 3 \text{ meV},$$

in good agreement with the value deduced for $\hbar\omega$ by Hennel et al. [5] .

IV. Summary and Conclusions

In this paper, we observe a very strong field dependence of the electron emission rate e_n from the chromium deep level in GaAs. At a temperature of 400 K, for example, an electric field as small as 7×10^4 Vcm^{-1} is sufficient to double the rate e_n above its zero field value, while a field of 4×10^5 V cm^{-1} can enhance e_n by as much as 25 orders of magnitude at 120 K. The measured values of e_n are accurately accounted for by our phonon assisted tunneling model. A closest fit method yields the value of $S\hbar\omega$ with a small uncertainty ; however, the model is tolerant to wide variations in $\hbar\omega$. The value of $S\hbar\omega$ and the range of acceptable values for $\hbar\omega$ are found to be consistent with optical data and with an estimate based on electron capture cross-section measurements and a formula proposed by Burt.

The above remarks show that a remarkable coherence can be obtained in describing different phenomena related to lattice relaxation for the Cr level as has already been seen for other levels in GaAs and GaP [2] .

References

1) G.M. Martin, A. Mitonneau, D. Pons, A. Mircea and D.W. Woodard : J. Phys. C, Solid State Physics, 13 (1980) 3855.
2) S. Makram-Ebeid : to be published in Appl. Phys. Lett., September 1980.
3) D. Pons and S. Makram-Ebeid : J. Phys. Appl. (France), 40, (1979) 1161.
4) S. Makram-Ebeid and M. Lannoo : to be published.
5) A.M. Hennel, W.S. Szuszkiewicz and G. Martinez : to be published.
6) B.K. Ridley : J. Phys. C; Solid State Physics, 11 (1978) 2323.
7) M.G. Burt : J. Phys. C, Solid State Physics, 12 (1979) 4827.
8) T. Jesper, B. Hamilton, A.R. Peaker : Semi-insulating III-V Materials Conf., Nottingham, April (1980), to be published in Proceedings.
9) A. Mitonneau, A. Mircea, G.M. Martin and D. Pons : Rev. Phys. Appl. (France), 14 (1979) 853.