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THEORETICAL SECONDARY EMISSION YIELD OF CESIATED GALLIUM ARSENIDE*

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ABSTRACT

The secondary emission coefficient of p-type GaAs cleaved in vacuum and treated with Cs and (O+Cs) layers is calculated. A very simple approach is used to determine the generation of internal secondaries, and a diffusion model for two conduction band valleys (Γ_1 and X_1) based on photoemission work is used to calculate the secondary current near the exit surface. The final escape of the two kinds of thermalized electrons through the treated surface is then considered. Secondary emission coefficients in excess of 1000 at primary energies just above 20 keV are predicted. The validity of the theoretical model is established by comparison with a simpler theory which predicts experimentally verified values of yield for GaP. Useful applications for GaAs secondary emitters are then discussed.

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Recent detailed work on the high quantum efficiency photoemission from GaAs by James[1] and by James and Moll[2] reveals that properly treated GaAs has great potential as a very high yield secondary emitter: Excited conduction electrons thermalize into one of the two valleys, Γ_1 at approximately 1.38 eV, and X_1 at approximately 1.75 eV above the top of the valence band. The room temperature diffusion length L_Γ for electrons in the Γ_1 valley is $1.6 \pm .2$ microns for boat-grown 1×10^{19} p-type GaAs (Zinc doped) while in the X_1 valley L_X is approximately 0.03 microns. The large value of L_Γ indicates that secondary electrons generated as deep as 20,000 Å inside the material have a good chance to diffuse to the band bending region near the surface, caused by the Cs and (O + Cs) treatments. For the optimum surface treatments, James[1] finds that the probability of escape of such electrons through the surface layer is $P_\Gamma = 0.36$. Internal secondaries which thermalize in the X_1 minimum have a relatively short diffusion length (approximately 300 Å), but electrons disappearing from the X_1 valley appear on the Γ_1 valley where they still have a very long diffusion length. The minimum escape probability for X_1 electrons reaching the band bending region given by James is $P_X = .45$ at the optimum surface condition.

The above details show qualitatively that GaAs has very favorable transport properties for internal secondaries. In addition, a study of secondary emission in alkali halides by Llacer and Garwin[3] reveals the advantage of a material with low band gap and high average atomic number and density in the generation of internal secondaries. From this point of view, GaAs should have an advantage over GaP, whose secondary emission characteristics have been studied by Simon and Williams.[4]

The quantative analysis of secondary yield can begin by considering the generation of internal secondaries. The energy lost by the primary electrons in the emitter material can be represented in a useful approximation as being uniform up to a depth x_0, usually called the range of the primary particle. For $x > x_0$, the energy loss is taken to be zero. This approximation is based on the work of Young[5] on electron transmission through films of Al_2O_3 and it should apply moderately well to reflection secondary emission, as the discussion in Sect. II, Ref. 3 indicates.

Defining $\bar{e}$ as the average primary energy loss needed to generate one excited electron, a generation function $G = E_p/(\bar{e}x_0)$ can be defined for $0 < x < x_0$, and zero elsewhere. E_p is the primary energy. The value of x_0 can be obtained from the range-energy relation[3]

$$x_0 = 1350\,(E_p^{1.3}/\rho) \qquad (\text{Å}) \qquad (1)$$

for E_p in keV, and the density ρ in g/cc.

The average energy loss $\bar{e}$ can be estimated by considering the ratios between $\bar{e}$ and E_g for materials with bulk characteristics not very different from GaAs. The values of $\bar{e}$ are obtainable by observing the current pulses generated in reverse biased p-n junctions used as radiation detectors when a charged particle deposits all its energy in the depletion region.

Table I summarizes the results for Ge, Si, and GaP, giving an average value for $\bar{e}/Eg$ of approximately 3.55 with little dispersion. For a band gap of 1.38 eV, the estimate for GaAs is then $\bar{e} = 4.9$ eV of primary energy loss per electron excited. Those electrons generated with initial energies between the Γ_1 and the X_1 minima will thermalize in the Γ_1 valley, while the rest will thermalize in the X_1 valley before escaping the material or decaying into the

Γ_1 minimum. Following James' notation, the fraction of electrons initially thermalizing in the lower valley will be labeled F_Γ, while $F_X = 1 - F_\Gamma$.

The transport of thermalized secondaries can then be studied with simple coupled diffusion equations. The fact that a fraction of secondaries can reach the band bending region before thermalizing (particularly at low E_p) will be ignored. The diffusion equation for the X_1 valley is solved first. The problem contains two regions, for x larger or smaller than x_0 :

$$- D_X \frac{d^2 n_X}{dx^2} + \frac{n_X}{\tau_X} = \begin{cases} F_X G & \text{for} \quad 0 < x < x_0 \\ 0 & \text{for} \quad x > x_0 \end{cases} \tag{2}$$

D_X is the diffusion constant, n_X is electron density, and τ_X is the lifetime of the electrons in the X_1 valley. Boundary conditions for the solution area : at $x = 0$ it is required that $n_X = 0$, and at $x = x_0$, n_X and its derivative must be continuous (no infinite current sinks). The solution to Eq. (2) is then

$$n_{X1} = F_X G \tau_X \left\{ 1 - \left[1 - (1/2\,\alpha)\right] \left[\exp(-x/L_X)\right] - (1/2\,\alpha) \left[\exp(x/L_X)\right] \right\} \tag{3.1}$$

$$\text{for } 0 < x < x_0$$

and

$$n_{X2} = F_X G \tau_X \left\{ \left[(1/2\,\alpha) + (\alpha/2) - 1\right] \left[\exp(-x/L_X)\right] \right\} \quad \text{for } x > x_0 \tag{3.2}$$

where $L_X = (D_X \tau_X)^{\frac{1}{2}}$ and $\alpha = \exp(x_0/L_X)$.

The X_1 current at the band bending region, $x = 0$, is then obtained from Eq. (3.1) by

$$J_X = D_X \left. \frac{dn_{X1}}{dx} \right|_{x=0} = F_X G L_X \left[1 - (1/\alpha)\right] \tag{4}$$

and the secondary yield δ_X due to current in the X_1 valley is obtained by multiplying J_X by the escape probability P_X. The assumption is made here that electrons reflected back from the surface into the material do not perturb the diffusion solution substantially.

The diffusion equation for the Γ_1 valley has as driving terms the fraction of internal secondaries which thermalizes directly in it, given by $F_\Gamma G$, and the rate at which electrons are lost from the X_1 valley and appear in the Γ_1 valley. Therefore,

$$-D_\Gamma \frac{d^2 n_\Gamma}{dx^2} + \frac{n_\Gamma}{\tau_\Gamma} = \begin{cases} F_\Gamma G + (n_{X1}/\tau_X) & \text{for } 0 < x < x_0 \\ n_{X2}/\tau_X & \text{for } x > x_0 \end{cases} \tag{5}$$

The solution to Eq. (5) is obtained with boundary conditions identical to those of Eq. (2) and the current at $x = 0$ is given by

$$J = GL_\Gamma[1 - (1/\beta)] + F_X G L_X \left\{ \frac{(1/2\alpha) + (1/2\beta) - 1}{1 + (L_X/L_\Gamma)} + \frac{(1/2\alpha) - (1/2\beta)}{1 - (L_X/L_\Gamma)} \right\} \tag{6}$$

where $L_\Gamma = (D_\Gamma \tau_\Gamma)^{\frac{1}{2}}$, and $\beta = \exp(x_0/L_\Gamma)$.

The first term of Eq. (6) has the same form as the solution to the X_1 equation, and corresponds to the diffusion current which one would obtain if all the generated secondaries thermalized directly into the Γ_1 valley. The second term in Eq. (6) corresponds then to the corrections due to the fact that a fraction F_X is first thermalized in the X_1 valley and, when generated near enough to the exit surface, can escape before decaying to the Γ_1 minimum. For $L_X \ll L_\Gamma$, this correction is primarily the diffusion

current in the X_1 valley at x = 0, Eq. (4), as can be seen by letting $L_X/L_\Gamma \ll 1$ in Eq. (6) and dropping second order terms in L_X/L_Γ. The result is

$$J_\Gamma = GL_\Gamma\left[1 - (1/\beta)\right] - F_X GL_X\left[1 - (1/\alpha)\right] \tag{7}$$

The external secondary yield from the Γ_1 valley, δ_Γ, is again obtained by multiplying J_Γ times the escape probability P_Γ.

A comparison of the form of the single valley solution in the present diffusion model, Eq. (4), with that obtained by Simon and Williams[4] in their analysis of the secondary emission properties of GaP (single valley material) by a more conventional method shows an equivalence of the expressions for yield, but not of the concepts involved. Their escape depth for secondaries is equivalent to the diffusion length, and the product of their empirical constants B_1B_2 (coefficient which takes into account that only a fraction of excited electrons diffuse toward the surface, and probability of escape through the surface barrier, respectively) corresponds to the escape probability P used in the present work. Simon and Williams use $B_1B_2 = 0.5$ in order to fit their experimental data, and this is a reasonable number for P in the diffusion approach. From photoemission, the value of L for GaP is 2000 Å. Because of the equivalence between the two formulations and the fact that Simon and Williams have obtained good agreement between their theory and experiments (limited to a few keV of primary energy by their measuring equipment), it is felt that the diffusion theory can be extended to the two valley material GaAs.

Computations of yield as a function of primary energy for GaAs showing the contributions of the Γ_1 and X_1 valleys have been carried out in accordance with the above model, using the parameter values obtained from photoemission

by James.[1] This computation does not have any adjustable parameters. Figure 1 shows the results obtained for a fraction $F_\Gamma = 0.25$ of electrons thermalizing in the Γ_1 valley initially. Changes in F_Γ between 0 and 0.5 affect δ_X and δ_Γ individually to some extent only at low E_p, although the total yield is hardly affected. The yield of GaP is also shown for comparison. It must be pointed out that the results for GaP are not identical to those published by Simon and Williams,[4] particularly above 2 keV, due to the fact that those authors took a density of 5.35 g/cc instead of 4.13 for GaP.

From the results of Fig. 1 it is clear that in applications in which primary energies are not high (up to 1 keV), as in electron multiplier structures, little difference can be expected between the performance of GaAs and GaP. In fact, the more difficult and exacting surface treatments needed for GaAs make that material less desirable than GaP for such applications. However, in applications with deeply penetrating primary particles, the superiority of GaAs is apparent. For example, for minimum ionizing particles, an average secondary yield of approximately 50 is expected. The development of techniques for stable surface treatments is therefore very desirable. These techniques are identical to the ones needed for GaAs infrared photoemitters on which a substantial amount of work is now being carried out in industrial and research laboratories. Measurements to verify the expected high yields of GaAs are now being prepared at the Stanford Linear Accelerator Center.

LIST OF REFERENCES

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TABLE I

Characteristics of Three Materials at T = 300°K

Material	E_g (eV)	$\bar{e}$ (eV)	Reference	$\bar{e}/E_g$
Ge	0.79	2.8	6	3.55
Si	1.09	3.6	6	3.3
GaP	2.26	8.7	7	3.85

FIGURE CAPTION

1. Theoretical secondary emission yield of GaAs, showing contributions from the Γ_1 and X_1 valleys. Also, calculated yield of GaP for comparison.

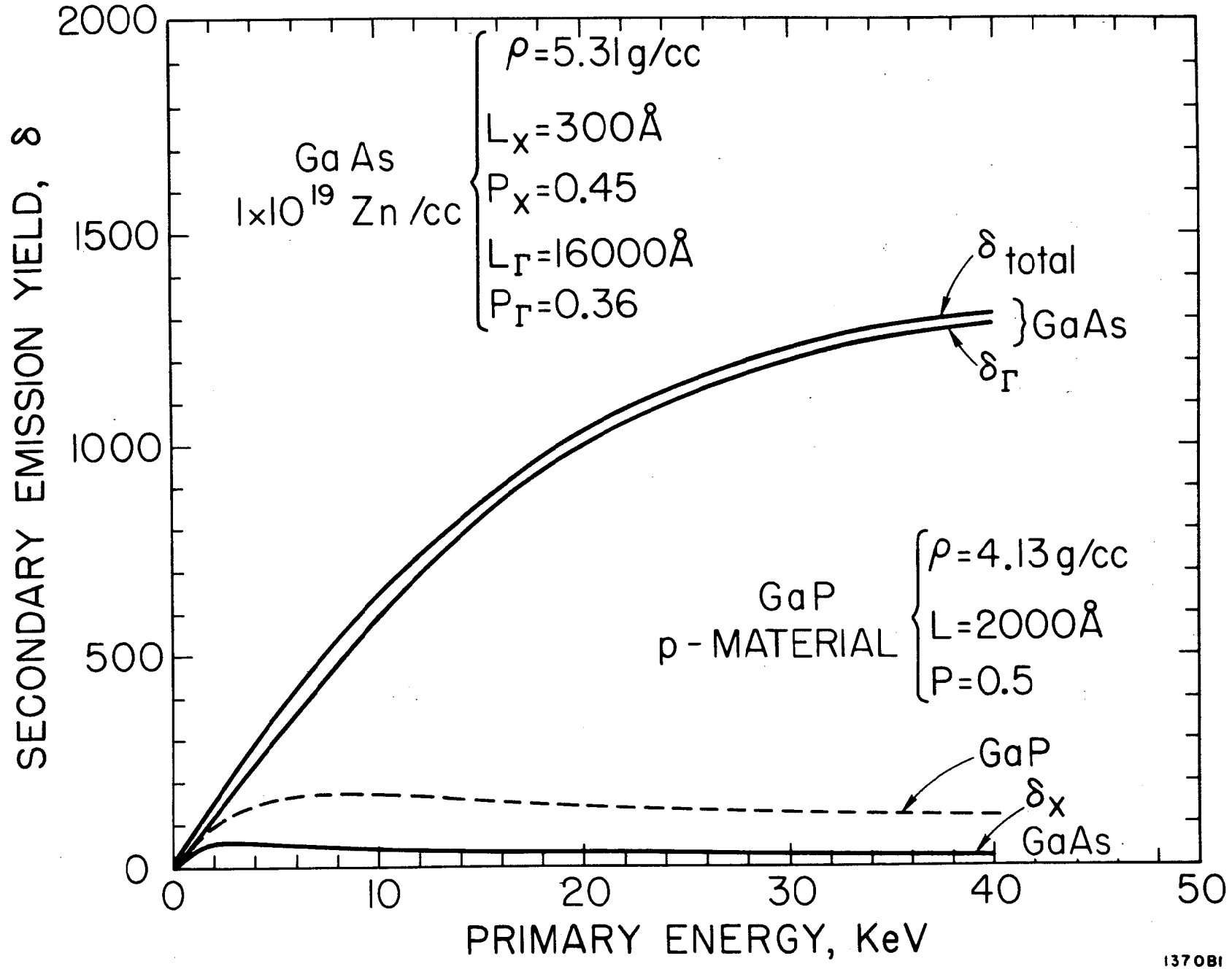
2000
1500
1000
500
0
SECONDARY EMISSION YIELD, δ
0
10
20
30
40
50
PRIMARY ENERGY, KeV
GaAs
1×10^19 Zn/cc
ρ=5.31 g/cc
Lx=300Å
Px=0.45
Lr=16000Å
Pr=0.36
δ total
δr
GaAs
GaP
p-MATERIAL
ρ=4.13 g/cc
L=2000Å
P=0.5
GaP
δx
GaAs
137081

Fig. 1