Semicond. Sci. Technol. 4 (1989) 498–499. Printed in the UK

LETTER TO THE EDITOR

# Calculation of quantum efficiency of field-assisted transmission-mode GaAs photocathodes

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Received 2 March 1989, accepted for publication 21 March 1989

**Abstract.** The quantum efficiency of field-assisted transmission-mode GaAs photocathodes has been calculated. The results show that supplying an electric field across a photocathode is an efficient way to greatly increase the quantum efficiency of transmission-mode GaAs photocathodes.

Quantum efficiency is one of the most important parameters of photocathodes. In previous research, the quantum efficiency of transmission-mode GaAs photocathodes has already been calculated [1, 2], and the idea of field-assisted photocathodes has also been proposed [1]. However, the previous work did not provide the results of calculations or the relationship between the quantum efficiency and the electric field in detail. Here, we calculate the quantum efficiency of transmission-mode GaAs photocathodes with varying electric field, which is supplied across the photocathodes. The results indicate that the quantum efficiency can be greatly increased with the electric field. We hope that the results will be helpful in further improving the quantum efficiency of transmission-mode GaAs photocathodes.

Figure 1 shows an energy band diagram used in the calculation. The direction of the electric field is from the emission surface toward the inside of cathodes. The electrons at the top of the valence band absorb incident photons, jump into the conduction band and become photoelectrons. As the photoelectrons diffuse toward the emission surface, they also drift toward the emission surface under the action of the electric field $\boldsymbol{E}$. If we consider the motion of the photoelectrons only in the $x$ direction and assume that the field is a uniform electric field, the distribution of photoelectrons in the GaAs active layer is determined by

$$D_n \frac{\mathrm{d}^2\Delta n(x)}{\mathrm{d}x} - \mu_n|E| \frac{\mathrm{d}\Delta n(x)}{\mathrm{d}x} - \frac{\Delta n(x)}{\tau_n} + (1-R)\,\frac{N}{A}\,\alpha \exp(-\alpha x) = 0 \qquad (1)$$

where $\Delta n(x)$ is the concentration of the photoelectrons; $D_n$ is the diffusion coefficient of the photoelectrons, $\tau_n$ and $\mu_n$ are the photoelectron lifetime and mobility respectively, $R$ and $A$ are the photocathode reflection coefficient and illuminated area respectively, $N$ is the incident photon flux and $\alpha$ is the absorption coefficient of GaAs.

From equation (1), we get

$$\Delta n(x) = B_1 \exp(\beta_1 x) + B_2 \exp(\beta_2 x) + \gamma \exp(-\alpha x) \qquad (2)$$

where

$$\beta_1 = \frac{1}{2L_n^2}\left[\mu_n\tau_n|E| + \sqrt{(\mu_n\tau_n|E|)^2 + 4L_n^2}\right] \qquad (3)$$

$$\beta_2 = \frac{1}{2L_n^2}\left[\mu_n\tau_n|E| - \sqrt{(\mu_n\tau_n|E|)^2 + 4L_n^2}\right] \qquad (4)$$

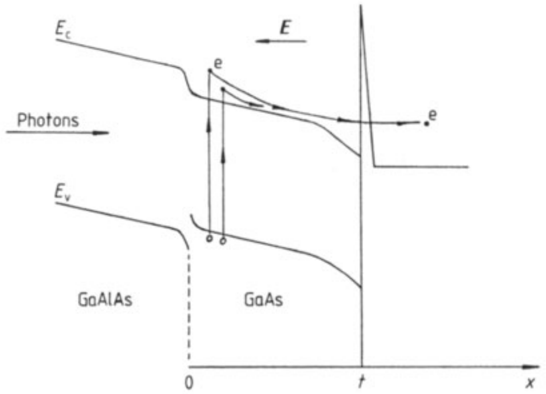

**Figure 1.** The energy band diagram of field-assisted transmission-mode GaAs photocathodes.

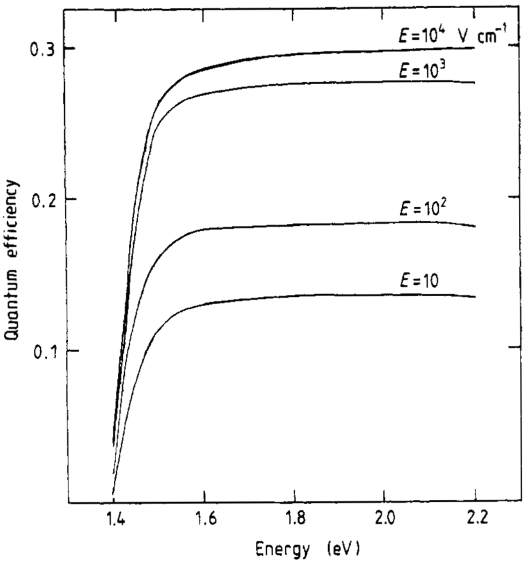

**Figure 2.** Relationship between the quantum efficiency and the energy of incident photons with varying electric field.

$$\gamma=-\frac{N}{D_nA}(1-R)\frac{\alpha L_n^2}{\alpha^2L_n^2+(g/kT)\alpha|\boldsymbol{E}|L_n^2-1} \tag{5}$$

and

$$L_n=(D_n\tau_n)^{1/2}.$$

$B_1$ and $B_2$ are coefficients to be fixed.

Generated by incident light, $\Delta n(x)$ must be finite when $|\boldsymbol{E}|$ tends to be infinite. So we ought to have

$$B_1=0.$$

At $x=0$ $\Delta n(x)$ is satisfied, with the following border condition:

$$D_n\frac{\mathrm{d}\Delta n(x)}{\mathrm{d}x}\bigg|_{x=0}-\mu_n|\boldsymbol{E}|\Delta n(0)=S\Delta n(0) \tag{6}$$

where $S$ is the recombination velocity of electrons at the GaAs/GaAlAs interface.

Substituting equation (2) in equation (6), we have

$$B_2=\frac{D_n\alpha+S+\mu_n|\boldsymbol{E}|}{D_n\beta_2-S-\mu_n|\boldsymbol{E}|}\gamma \tag{7}$$

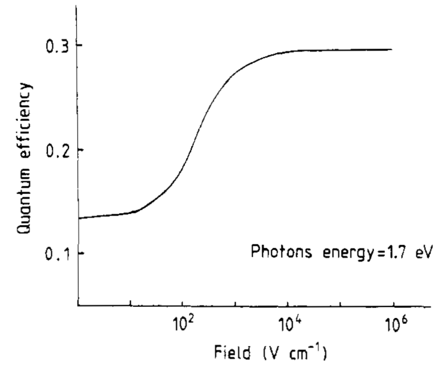

**Figure 3.** Relationship between the quantum efficiency and the strength of the electric field.

$$\Delta n(x)=\gamma\left(\frac{D_n\alpha+S+\mu_n|\boldsymbol{E}|}{D_n\beta_2-S-\mu_n|\boldsymbol{E}|}\exp(\beta_2x)+\exp(-\alpha x)\right). \tag{8}$$

The flux of photoelectrons emitted by photocathodes is

$$J=P\left(-D_n\frac{\mathrm{d}\Delta n(x)}{\mathrm{d}x}\bigg|_{x=t}+\mu_n|\boldsymbol{E}|\Delta n(t)\right) \tag{9}$$

where $P$ is the probability of emission.

The quantum efficiency of photocathodes is

$$\rho=J/(N/A). \tag{10}$$

Substituting equation (8) in equation (9), and then in equation (10), we have the quantum efficiency of field-assisted transmission-mode GaAs photocathodes.

$$\rho=\frac{P(1-R)\alpha L_n^2}{\alpha^2L_n^2+(q/kT)\alpha|\boldsymbol{E}|L_n^2-1}$$
$$\times\left(\frac{D_n\alpha+S+\mu_n|\boldsymbol{E}|}{D_n\beta_2-S-\mu_n|\boldsymbol{E}|}[\beta_2-(q/kT)|\boldsymbol{E}|]\exp(\beta_2t)\right.$$
$$\left.-[\alpha+(q/kT)|\boldsymbol{E}|]\exp(-\alpha t)\right).$$

Figure 2 shows the relationship between the quantum efficiency and the energy of incident photons with varying electric field. Figure 3 shows the change of quantum efficiency with electric field, while the energy of incident photons is constant.

The energy responsive region of transmission-mode GaAs photocathodes is from 1.4 eV to 2.2 eV determined by the energy band gap of GaAs and GaAlAs. From figures 2 and 3, we can see that the quantum efficiency is increased within the whole responsive region by applying an electric field, and it can be 2.2 times greater than that without the field. From figure 3, we also know that when the strength of the field varies from 100 V cm$^{-1}$ to $5\times10^3$ V cm$^{-1}$, the quantum efficiency rises sharply; however, it tends to saturate while the strength is over $10^4$ V cm$^{-1}$. That is because all the photoelectrons generated inside are 'swept out' by the electric field when its strength is sufficiently large, which saturates the emitted photoelectrons. On the other hand, it tells us that it is efficient to supply an electric field from 100 V cm$^{-1}$ to $10^4$ V cm$^{-1}$, but not above $10^4$ V cm$^{-1}$, in order to increase the quantum efficiency.

As mentioned above, the calculation predicts that applying an electric field across a photocathode, the direction of which is from the emission surface toward the inside, is an efficient way to increase the quantum efficiency of transmission-mode GaAs photocathodes.

## References

[1] Bell R L 1973 *Negative Electron Affinity Devices* ch. 6 (Oxford: Clarendon)

[2] Rougeot H and Baud C 1979 *Negative Electron Affinity Photoemitters, A.E.E.P.*, vol. 48, pp 1–35