SLAC–PUB–5896
September 1992
(A/E)

NONLINEAR EFFECTS IN PHOTOCATHODES *

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ABSTRACT

Recent experiments at the Stanford Linear Accelerator Center (SLAC) [1] have demonstrated that the photoemitted number of electrons from a cesium-activated gallium arsenide (GaAs) crystal saturates at high incident flux, becoming insensitive to the incident photon flux at high intensity. This article offers a physical model that attempts to explain this phenomenon. A comparison of experimental data versus model predictions is also included.

Submitted to *Applied Physics*

* Work supported in part by Department of Energy contract DE–AC03–76SF00515.

In the photoemission process, virtually all incident photons give rise to electron-hole pairs. SLAC electron intensity specifications require the emission of 10^{11} electrons per square centimeter in a 2 ns laser pulse of wavelength 715 nm [2]. For this wavelength, the absorption length in GaAs is $L_{\rm ab} \sim 0.5$ m [3], while a typical SLAC GaAs photocathode has quantum efficiency (at low photon flux) of $\sim 1\%$. Thus, in the limit that the laser pulse duration is much less than both the electron-hole recombination and heavy particle (hole) diffusion times, an electron-hole plasma with density $n = 210^{17}$ cm^{-3} is created in the semiconductor.

We suggest that the presence of this plasma reduces the quantum efficiency of high intensity photoemission by increasing the work function encountered by electrons leaving the material. This increase is given by $\Delta W = W_p = e^2/r$, where r is the Debye radius, given by $1/r^2 = 8\pi\, e^2\, n/\epsilon T$, where $n = N_{\rm ph}/L_{\rm ab}$, $N_{\rm ph}$ is the area density of incident photons, and ϵ the permeability constant of the crystal. For GaAs, this estimate yields $W_p \sim 0.2\,(I)^{1/2}$ eV, where I is the laser intensity in μJ/cm^2.

This plasma work function W_p modifies the intrinsic work function of GaAs, W. The application of a cesium monolayer also modifies the work function, reducing it by $W_{\rm Cs} = (4\pi e^4 N_{\rm Cs}/\epsilon)^{1/2}$, where $N_{\rm Cs}$ is the area density in the monolayer. Finally, the photo cathode is operated in an external accelerating electric field E, which reduces the work function (Shottky effect) by

$$W_{\rm Sh} \;=\; (e^3 E)^{1/2} \; . \tag{1}$$

The total work function is thus given by

$$W_{\rm tot} \;=\; W - W_{\rm Cs} - W_{\rm Sh} + W_p \; . \tag{2}$$

To calculate the resulting quantum efficiency it is necessary to include the effective electron temperature T_e. Let us suppose that quantum efficiency for $q << 1$ depends on the work function in the following natural way:

$$q = \exp(-W_{\rm tot}/T_e) \ . \tag{3}$$

For 715 nm laser light, electrons are excited into the conduction band with an energy of ~ 0.3 eV. Since the phonon-electron collision time is short ($\sim 10^{-13}$ s), these electrons quickly thermalize to the ambient crystal temperature (T = 26 meV).Essentially all electrons are thermalized. When they are accelerated in the depletion region, they undergo scattering, resulting in some effective temperature, i.e., energy spread of the electrons. This energy spread has been measured [4] using a spectrometer. Electrons not excaping to vacuum are assumed to be trapped in time shorter than pulse duration. Thus electron emission should be dominated by "fresh" electrons which have not trapped. For this reason, the photo emission current is given by

$$dN_e \,/\, dt \ = \ q(t)\, dN_{\rm ph} \,/\, dt \ ; \tag{4}$$

i.e., the current is proportional to the instantaneous, rather than accumulated, incident photon flux.

In the limit that the laser pulse is short with respect to the plasma recombination and diffusion times, the plasma work function W_p is proportional to the square root of the accumulated photon flux. Applying this to the above expression (4) for the quantum efficiency yields the following expression for the total electron yield N_e

$$\begin{aligned} N_e &= q_0 \int \exp\{-\sqrt{\alpha N_{\rm ph}}\,\}\, dN_{\rm ph} \\ &= 2\,\frac{q_0}{\alpha}\ \left[1 - \exp\{-\sqrt{\alpha N_{\rm ph}}\,\}\left(1 + \sqrt{\alpha N_{\rm ph}}\right)\right] \ , \end{aligned} \tag{5}$$

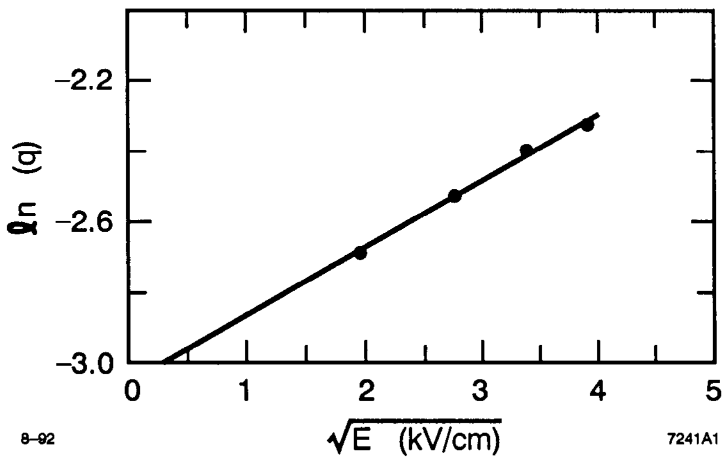

Figure 1. Quantum efficiency as a function of the cathode external electric field [1]. Fit corresponds to the effective electron temperature of 68 meV (Shottky dependence).

where $q_o = \exp\{-(W - W_{\mathrm{Cs}} - W_{\mathrm{Sh}})/T_e)\}$ is the low-intensity quantum efficiency, and

$$\alpha \;=\; 8\pi\; e^6 \,/\, T(T_e)^2\; \epsilon L_{\mathbf{ab}}\;. \tag{6}$$

Thus, at high intensity, the total electron yield approaches the limiting value $2q_o/\alpha$. The total electron density is limited by α. The only truly unknown value in formula (6) is T_e. We extract it from Shottky dependency data, Fig. 1, which shows a plot of $ln(q)$ versus $\sqrt{E}$) from the SLAC data. The slope of this line yields the effective electron temperature T_e = 68 meV via the expression derived from Eqs. (1)–(3).

$$ln(q) \;=\; C + \sqrt{e^3\,E}\,/\,T_e\;. \tag{7}$$

Substituting this value of T_e into formula (6) gives us$a = 1.1 \times 10^{-12}$ cm^2. Thus,the maximum number of electrons which may be extracted from the photocatode is

$$N_e \;=\; 1.8\; q_o\; 10^{12}\; e/\mathrm{cm}^2\;.$$

Formula (4) is easily generalized to the case for which the laser pulse duration is not short with respect to the plasma recombination and diffusion times, for which the electron yield is given by

$$\dot{N}_e \;=\; q_0\; \dot{N}_{ph} \exp\{-\sqrt{\alpha\, L_{ab}\, n(t)}\}\;, \tag{8}$$

where$n(t)$ is the plasma density, taking into account the effects of recombination and diffusion. In the steady-state condition, maximum electron flux is

$$\dot{N}_{e\;\mathbf{max}} \;=\; \frac{4q_0}{\alpha\tau e^2}\;; \qquad for \qquad \dot{N}_{ph} \;=\; \frac{4}{\alpha\tau}\;. \tag{9}$$

This simple model provides a number of predictions that can be addressed with the SLAC data:

(1) The logarithm of the quantum efficiency is proportional to the square root of the external electric field.

(2) The total electron yield is proportional to the low intensity quantum efficiency q_o. All saturation curves are identical up this scale factor q_o.

(3) Total charge limit is proportional to T and T_e^2, measured from the Schottky effect.

(4) For a crystal with recombination time on the order of the laser pulse duration, the total electron yield increases with decreasing recombination time. Thus, for a heavily doped crystal, the yield increases with the doping fraction.

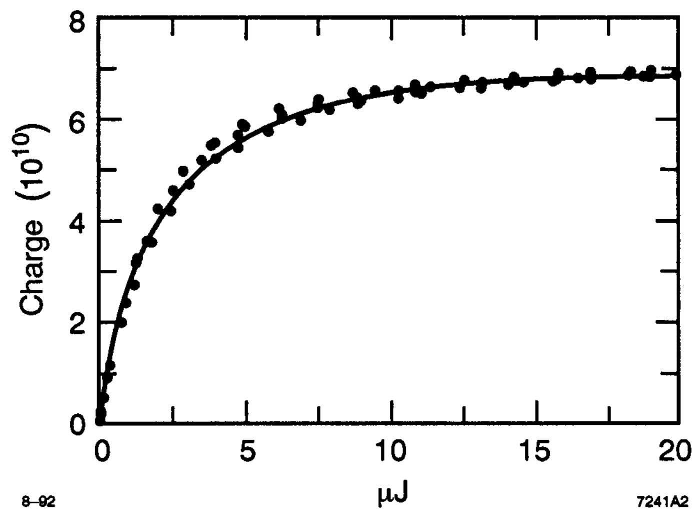

Figure 2. Experimental data [1] fit. All experimental data are normalized to one percent quantum efficiency.

Figure 1 shows a plot of $ln(q)$. The predicted linear dependence is observed.

Figure 2 shows the dependencies of the SLAC electron yield as a function of laser pulse energy for a cathode with low-intensity quantum efficiency, $q_o = 0.49\%$, 0.46%, 0.42%, and 0.1%. Data is normalized by dividing the electron yield by the quantum efficiency. One can see from the data points that yields proportion of the low intensity quantum efficiency confirms the prediction of this model. Also shown is a curve fit to the form of Eq. (8) where $n(t)$ is solution

$$(dn/dt) + (n/\mathcal{T}_r) - (1/L_{\rm ab})\,(dN_{\rm ph}/dt) \;=\; 0 \;,$$

where the α and recombination time $\mathcal{T}_r$ are left as free parameters. The resulting value $a = 1.2 \times 10^{-12}$ cm^2 is in good agreement with the theoretical value , while the value $\mathcal{T}_r$ = 1.9 ns is reasonable for the level of doping of the cathode under study ($\sim 2 \times 10^{19}$ atom/cm^3) [3].

In conclusion, we have offered a physical model which attempts to explain non-linear effects observed in photoemmission from a GaAs photo cathode at SLAC. This model incorporates a change in the work function caused by the formation of an electron-hole plasma within the semiconductor cathode at high laser intensity. Calculations based on this model give good quantitative agreement with the SLAC observations.

ACKNOWLEDGMENTS

The author thanks J. Clendenin, J. Frish, S. Heifets, A. Kulikov, T. Maruyama, B. Shumm, M. Woods and G. Zapalac for useful discussions.

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