EFFECT OF SURFACE ROUGHNESS ON THE EMITTANCE FROM GaAs PHOTOCATHODE*

S. Karkare†, I. Bazarov, L. Cultrera, A. Iyer, X. Liu, W. Schaff
CLASSE, Cornell University, Ithaca, New York, USA

Abstract

The surface roughness of GaAs photocathodes used in the injector prototype for the ERL at Cornell University was measured and compared to that of the atomically polished GaAs crystal surface using the atomic force microscopy (AFM) technique. The results show at least an order of magnitude rise in the GaAs surface roughness after subjecting it to heat cleaning, prior to activation. An analytical model for photoemission that takes into account the effect of surface roughness has been developed. This model predicts emittance values close to the experimental observations, explains the experimentally observed variation of emittance with incident light wavelength and reconciles the discrepancies in experimental data.

INTRODUCTION

GaAs activated to negative electron affinity (NEA) via cesiation is a high quantum efficiency (QE) photocathode and can be effectively used for high brightness electron beams from photoinjectors [1, 2]. Although, the properties of GaAs as a photocathode have been studied for decades [3, 4, 5], the mechanism of photoemission from these photocathodes is not well understood.

Normalized transverse rms emittance (ϵ_{nx}) is related to the mean transverse energy (MTE) and the spot size of the laser (σ_x) by $\epsilon_{nx} = \sigma_x\sqrt{\text{MTE}/(m_e c^2)}$ where $m_e c^2$ is the rest mass energy of a free electron. Discrepancies exist between mean transverse energy (MTE) predictions from different theoretical models of photoemission and also the experimental data [6]. These are reconciled by a model of photoemission which incorporates the effects of the surface roughness [6]. Furthermore, the dependence of MTE on the wavelength of incident light [2], which other photoemission models fail to explain, can be explained by this rough cathode photoemission model [6].

However, the rough cathode photoemission model as described in Ref. [6] relies heavily on cumbersome simulations of tracking electrons launched from the surface of the cathode. In this paper, we develop an analytical expression for MTE using the rough cathode model. This enables a clear understanding of MTE dependence on the surface roughness characteristics, negative affinity, and the electric field applied at the surface. It also allows easy estimation of the MTE for a given surface with a known negative affinity and the electric field.

We also discuss the effect of heat treatment on the surface roughness of GaAs. Our measurements show that the surface roughness of GaAs increases drastically with temperature when heated beyond 580°C.

SURFACE ROUGHNESS OF GaAs

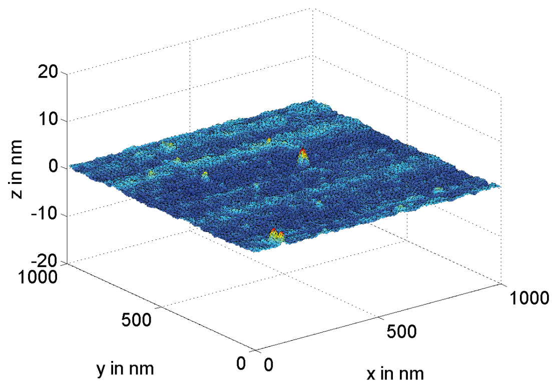
Surfaces of an atomically polished GaAs wafer prior to activation or heat treatment and a GaAs wafer used in the Cornell dc photoemission gun were studied using atomic force microscopy (AFM). The activation and heat cleaning procedure that the wafer used in the gun underwent is described in Ref. [6]. Both surfaces have a mirror-like appearance and look perfectly flat under an optical microscope. Fig. 1 shows the AFM images of these two surfaces. The rms roughness of the polished surface is less than 0.5nm whereas that of the activated surface is more than 6nm, which is an order of magnitude greater. Heat treatment for 1-3 hours at a temperature of around 600°C was found to be the cause of the roughening.

Surface roughness of GaAs wafers was studied after keeping the wafers for two hours at various temperatures. The temperature was measured using a thermocouple located on the molybdenum puck in close vicinity to the wafer. This thermocouple was calibrated using the melting point of 6-9's pure aluminum (660°C). Measurements were also taken using a mono-wavelength pyrometer. The pyrometer was calibrated to 580°C by looking at the sudden change in the RHEED pattern of GaAs which occurs as a result of oxides leaving the surface at this temperature [7]. Fig. 2 shows the rms roughness of the surface as a function of temperature. It can be seen that the roughness is very small and nearly constant up to 580°C. But beyond 580°C there is a sudden rise in roughness with temperature. It is also the temperature at which oxides leave the GaAs surface and the temperature at which the dissociation of GaAs sets in [8, 7]. The dissociation of GaAs is a possible cause of this rise in roughness. It should be noted that all the samples, except the one which was heated up to 700°C, retained their mirror-like surface.

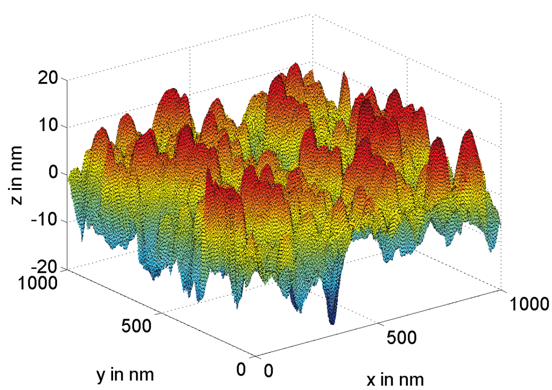
ROUGH CATHODE EMISSION MODEL

We treat the emission process as a refraction of Bloch waves at an ideal surface while largely ignoring scattering effects at the surface (the band-bending and activation regions) as done in Ref. [4]. Within this assumption, it is shown that the emitted electrons are distributed about the normal to the surface in a narrow conical distribution [6]

* This work is supported by NSF under Grant No. DMR-0807731 and DOE under Grant No. DE-SC0003965.
† ssk226@cornell.edu



(a) Surface of atomically polished GaAs crystal before heat cleaning (smooth surface)



(b) Surface of heat cleaned and activated GaAs crystal used in the Cornell dc photoemission gun (rough surface)

Figure 1: AFM images of GaAs surfaces.

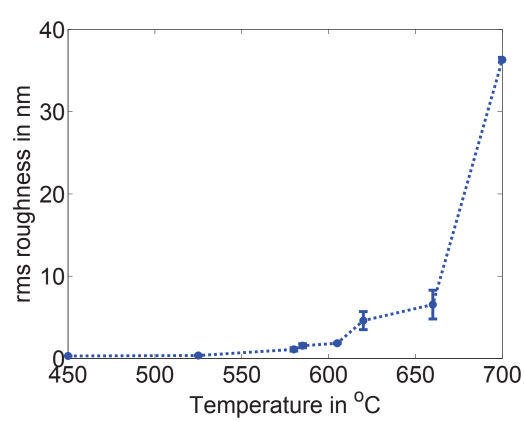


Figure 2: Surface roughness of GaAs vs. temperature.

given by

$$n(E,E_A,\theta)d\theta=\frac{(E+E_A)\cos\theta d\theta}{\sqrt{2E}\left(E-\frac{m_e}{m_\Gamma}(E+E_A)\sin^2\theta\right)^{1/2}} \tag{1}$$

where E is the energy of the electron relative to the Conduction Band Minimum (CBM) just inside the surface, E_A is the NEA of the surface, m_Γ is the effective mass of the electron in the Γ valley, m_e is the free electron mass and θ is the angle made by the trajectory of the electron with the normal to the surface at the point of launch. As a part of the rough cathode model, we assume that the axis of the cone is not in the direction of the normal to the global surface (direction of extraction of the electron beam), but is in the direction normal to the surface at the point of launch. This causes the electrons to have increased MTE and is called the slope effect [9]. MTE is further increased by the bending of the electric field near the surface. This is called the field effect [9]. The final MTE due to both the slope and field effects can be calculated by MTE$=(m_e\iint(v_{xs}+v_{xf})^2dxdy)/(\iint dxdy)$ where the integral is over the entire cathode surface, v_{xs} is the x-direction velocity at which electrons are launched from the surface and v_{xf} is the rise in x-direction velocity due to the bending of the electric field near the surface. This can be expanded to give MTE=MTE$_s$+MTE$_f$+MTE$_{sf}$ where MTE$_s$= $(m_e\iint(v_{xs})^2dxdy)/(\iint dxdy)$ is the MTE due to the slope effect only and MTE$_f=(m_e\iint(v_{xf})^2dxdy)/(\iint dxdy)$ is the MTE due to the field effect only and MTE$_{sf}$ = $2(m_e\iint(v_{xs}v_{xf})dxd)/(\iint dxdy)$

Calculation of MTE$_s$

Consider an infinitesimal area on the rough surface. Let α be the angle between the normal to this infinitesimal area and the normal to the global surface (direction of extraction of the electron beam). The MTE of electrons emitted from this surface is given by

$$T(E,E_A,\alpha)=\frac{(E+E_A)\int_0^{\theta_{max}}\int_{\phi_{min}}^{\phi_{min}} n(E,E_A,\theta)n_1(\phi,\alpha)\sin^2\phi\, d\phi d\theta}{\int_0^{\theta_{max}}\int_{\phi_{min}}^{\phi_{min}} n(E,E_A,\theta)n_1(\phi,\alpha)d\phi d\theta}$$

where ϕ is the angle between the direction of launch of an electron and the global normal, $n_1(\phi,\alpha)\,d\phi$ is the distribution of the ring of electrons at an angle θ about the local normal as seen from the global normal and $E+E_A=E_L$ is the energy at which electrons are emitted from the surface. This equation is integrated numerically for various energies of launch and angles α. The result can be fitted with the curve $T(E,E_A,\alpha)=(0.51E+0.5E_A)-(0.47E+0.5E_A)\cos(2\alpha)$ to less than a percent accuracy, α is in radians. The mean transverse energy for the entire surface is then given by

$$\mathrm{MTE}_s=\frac{\int_0^{\infty}\int_0^{\pi/2}T(E,E_A,\alpha)F(E)\,n_2(\alpha)d\alpha dE}{\int_0^{\infty}\int_0^{\pi/2}F(E)\,n_2(\alpha)d\alpha dE} \tag{2}$$

where $n_2(\alpha)$ is the distribution of angles α on the surface and $F(E)$ is the energy distribution of electrons just before emission from the surface and depends on the wavelength of incident light [6]. For infrared light wavelengths, $F(E)$ is the thermal distribution and

$$\mathrm{MTE}_s = (E_A + 1.4kT)\frac{\int_0^{\pi/2} n_2(\alpha)\sin^2\alpha d\alpha}{\int_0^{\pi/2} n_2(\alpha) d\alpha} + 0.066kT \quad (3)$$

where k is the Boltzmann constant and T is the temperature.

Calculation of MTE_f *and* MTE_{sf}

For the calculation of MTE_f and MTE_{sf}, we assume that all electrons are emitted exactly normal to the surface at the point of launch instead of being emitted in a cone about the normal. The surface can be expanded in its 2D Fourier components and can be written as $z = \sum_n A_n \phi_n(x,y)$. The electric potential near the surface is $U = E_0 z + \sum_n C_n e^{-z/p_n}\phi_n$ [10], where $p_n = (p_{nx}^2 + p_{ny}^2)^{\frac{1}{2}}$, p_{nx} and p_{ny} are periods in x and y directions respectively and E_0 is the longitudinal electric field away from the surface. If $p_n \gg A_n$ then $C_n \approx A_n E_0$ [10, 9]. Using the x-directional electric field calculated from this potential, the final x-directional velocity of electrons launched from the surface is given by $v_x = v_{xs} + v_{xf}$ [9]. $v_{xf} = \frac{e}{2m}\sum_n C_n \frac{d\phi_n}{dx} e^{k_1}\mathrm{erfc}(\sqrt{k_1})/k_2$ where $k_1 = \frac{E_L \cos^2\alpha}{2p_n E_0}$ and $k_2 = \sqrt{\frac{eE_0}{2\pi m_e p_n}}$. $v_{xs} = \sqrt{\frac{2E_L e}{m}}\cos\beta$ where β is the angle made by the electron launch velocity with the x-axis. Using these expressions MTE_f and MTE_{sf} are calculated by integrating numerically over the entire surface.

MTE *in the Slope Effect Limit*

For $E_0 < 5\mathrm{MV/m}$, $0.1\mathrm{eV} < E_A < 0.25\mathrm{eV}$ and the rough surface shown in Fig. 1 (conditions in the Cornell dc gun), we see that $\mathrm{MTE}_s \gg \mathrm{MTE}_f$. In this limit only the slope effect dominates and $\mathrm{MTE} \approx \mathrm{MTE}_s$ Fig. 3 shows the plot of MTE in the slope effect limit for thermalized electrons as a function of E_A for the two surfaces shown in Fig. 1 at different temperatures. We see that MTE is nearly an order of magnitude higher for the rough surface. Furthermore, MTE is sensitive to E_A only for the rough surface and more sensitive to the temperature for the smooth surface.

MTE *in the Field Effect Limit*

For near zero electron launch energies (E_L), $\mathrm{MTE}_f \gg \mathrm{MTE}_s$. In this limit $\mathrm{MTE} \approx \mathrm{MTE}_f$ and $k_1 \approx 0$. Thus

$$\mathrm{MTE}_f = \frac{eE_0\pi \sum_n A_n^2 p_n / p_{nx}^2}{8m_e \iint dxdy} \quad (4)$$

This limit is not practical for NEA photocathodes, but can be achieved in positive electron affinity cathodes.

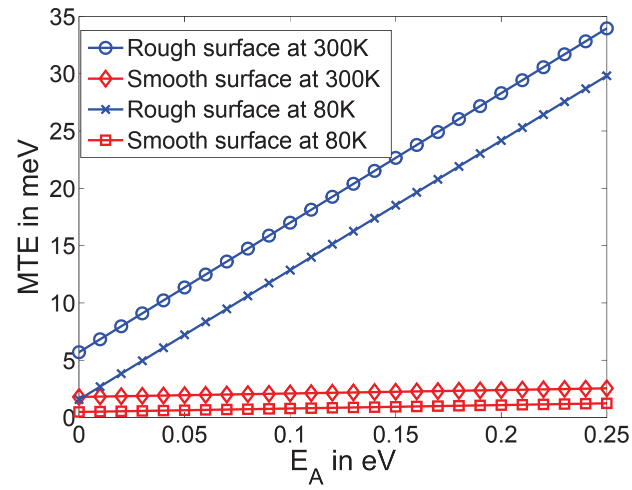


Figure 3: MTE in the slope effect limit vs. E_A for surfaces shown in Fig. 1 at different temperatures.

If E_0 is of the order of 50MV/m as in RF guns, none of the above limits apply and both MTE_s and MTE_f are comparable.

CONCLUSION

We see that the MTE is sensitive to NEA, a parameter which is difficult to control. This sensitivity along with the differences in surface preparation techniques can give rise to the inconsistency in the experimental data [6]. In summary, the nano-scale surface roughness of GaAs wafer plays an important role in the emittance and needs to be controlled by proper surface preparation procedures

REFERENCES

[1] D. H. Dowell et al., Nucl. Instrum. Methods Phys. Res. A 622, 685 (2010)

[2] I. V. Bazarov et al., J. Appl. Phys. 103, 054901 (2008).

[3] W. E. Spicer, Appl. Phys. A 12, 115 (1977).

[4] Z. Liu et al., J. Vac. Sci. Technol. B 23, 2758 (2005).

[5] S. Pastuszka et al., Appl. Phys. Lett. 71, 2967 (1997).

[6] S. Karkare and I. Bazarov Appl. Phys. Lett. 98, 094104 (2011).

[7] Y. Asaoka, Journal of Crystal Growth, 251, 40 (2003).

[8] F. Proix et al., J. Phys. C: Solid State Phys. 16, 5449 (1983).

[9] D.J. Bradley et al., J. Phys. D: Appl. Phys 10, 111 (1977).

[10] T. Gorlov, Journal of Electrostatics 65, 735 (2007).