QUANTUM EFFICIENCY, TEMPORAL RESPONSE AND LIFETIME OF A GAAS CATHODE IN SRF ELECTRON GUN

Erdong Wang, Peking University, China
Jörg Kewisch, Ilan Ben-Zvi, Andrew Burrill, Triveni Rao, Qiong Wu, BNL, Upton, NY 11973, U.S.A
Doug Holmes, AES, Medford, NY

Abstract

RF electron guns with a strained super lattice GaAs cathode can generate polarized electron beam of higher brightness and lower emittance than do DC guns, due to their higher field gradient at the cathode's surface. In a normal conducting RF gun, the extremely high vacuum required by these cathodes can not be met. We report on an experiment with a superconducting SRF gun, which can maintain a vacuum of nearly 10^{-12} torr because of cryo-pumping at 4.2K. With conventional activation, we obtained a QE of 3% at 532 nm, with lifetime of nearly 3 days in the preparation chamber. We plan to use this cathode in a 1.3 GHz, ½ cell SRF gun to study its performance. In addition, we studied the multipacting at the location of cathode. A new model based on the Fokker-Planck equation which can estimate the bunch length of the electron beam in the SRF gun is discussed in this paper.

INTRODUCTION

Future particle accelerators such as eRHIC and ILC require high brightness, high current polarized electrons Recently, using a superlattice crystal, the maximum polarization of 95% was reached [5]. Activation with Cs,O lowers the electron affinity and makes it energetically possible for all the electrons excited in to the conduction band and reach the surface to escape into the vacuum. Presently the polarized electron sources are based on DC gun, such as that at the CEBAF at Jlab. In these devices, the life time of the cathode is extended due to the reduced back bombardment in their UHV conditions. However, the low accelerating gradient of the DC guns lead to poor longitudinal emittance. The higher accelerating gradient of the RF gun generates low emittance beams. Superconducting RF guns combine the excellent vacuum conditions of the DC guns with the higher accelerating gradients of the RF guns and provide potentially a long lived cathode with very low transverse and longitudinal emittance.

In our work at BNL, we successfully activated the GaAs. The quantum efficient is 3% at 532 nm and is expected to improve further. In addition, we studied the multipacting at the location of cathode. A new model based on the Fokker-Planck equation which can estimate the bunch length of the electron beam in the SRF gun is discussed in this paper.

THE GAAS ACTIVATION

The preparation chamber for GaAs activation is a typical UHV chamber with capabilities to measure the chamber pressure, constituents of residual gas, heating of GaAs and exposing it to cs and O. Details on transferring the GaAs from the perparation chamber to the gun were published elsewhere [1].

The activation at 10^{-11} Torr base pressure is as follows: First, the GaAs crystal was heated up to 550C to 570C for 1 hour to ensure it had a super-clean surface. The vacuum pressure was maintained within the nanotorr range whilst the plug was heated. During this process, we warmed the SAES getter Cs dispenser with a current of 3A to avoid contaminating the source, but not hot enough to release Cs. We adopted the standard yoyo process where the sources of oxygen and Cs are opened and closed periodically. After applying the standard yoyo process, lowering the Cs dispenser's current to 4A for 10 minutes after the last peak, the photocurrents decrease and then enters a much more stable period compared to that after shutting off the Cs disperser with the appearance of the last peak. The highest quantum efficiency we obtained was 3.2% with a 532 nm laser. Currently, we are investigating the transfer of this cathode to the 1.3 GHz gun.

TEMPORAL RESPONSE OF CATHODE

The temporal response of photocathode is very important in the applications of an SRF gun. The simulation shows the ps response time makes the efficient acceleration in a 1.3GHz gun [2]. The time response is determined by the time spread between photo excitation and emission of electrons into the vacuum. In a photo cathode with a very short active region, the electrons produced by the laser pulse have a very small probability of interacting with each other before they are photoemitted. The escape of electrons from deeper in the material is due primarily to diffusion. However, in the RF gun it is speeded up by the RF field penetrating into the cathode [3]. Hartmann and his colleagues formulated a diffusion model to explain the bunch length in the DC gun [4]; that agreed well with the measurements and showed that the emission has a long tail around hundred picoseconds. In RF gun, the field-driven drift must be considered in describing its motion. The Fokker-Planck equation yields solution including both the drift and diffusion.

---

*Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. DOE

#wedwrd@gmail.com

Electrons that are free to move in the conduction band of the cathode in the RF gun experience several forces such as temperature gradient, RF fields and gradients in charge density.

The average particle's current density due to electric fields and diffusion is given by

$$\vec{J} = pq\mu\vec{E} + qD\nabla p \tag{1}$$

Where p is the average electron's density, q is the electric charge, μ is the electron's mobility, D is the drift constant and E is the electric field in the crystal.

With the three-step model, the movement of electrons in semiconductor is described by

$$\frac{\partial p(r,t)}{\partial t} = G(r,t) - \frac{p(r,t)}{\tau} + \frac{\nabla\cdot\vec{J}}{q} \tag{2}$$

The first term on the right side is a generation term. The crystal absorbs an incident laser pulse of intensity I_0 and Gaussian temporal shape.

$$G(z,t) = (1-r)I_0 e^{-[t-t_0/\tau_0]^2} e^{-\alpha z} \tag{3}$$

α determines the absorption coefficient of the crystal. I_0 is the intensity of the laser pulse incidenting in the semiconductor.

The second term represents electron annihilation wherein tau is the electron's lifetime.

The third term describes the electron displacement of electrons by diffusion and drift. The α and diffusion constant depend upon temperature and doping concentration of wafer.

Making the following simplifications and assumptions give us an equation for the initial and the boundary conditions. 1) The diameter of laser spot at the cathode usually is larger than absorption length. So, a one dimensional model describes the diffusion and drift. 2) The electron's recombination lifetime is orders of magnitude larger than the bunch length $\frac{p(r,t)}{\tau}$<<1. 3) In regions of no generation, the photo generation term is 0. In other places, it is expressed as the initial condition: $p(x,t=0) = p_0 e^{-\alpha x}$ for x[0,h] (2). 4) Negative electron affinity photoemitter with a band bending region at its activated surface.

Due to the surface effect, either most electrons that reach the semiconductor's surface lose energy in the bending region, becoming trapped at the surface or they are emitted from the cathode. However, they cannot diffuse back into the bulk. This fact can be taken into account by assuming a layer of limited thickness h with p(x,t)=0 on both surfaces of the layer.

P=0 for t>0 and x=0 and x=h

Then the simplified equation can be expressed as

$$\frac{\partial p(r,t)}{\partial t} = -\mu(r)\frac{\partial}{\partial x}[E_x p(r,t)] + D(r)\frac{\partial^2 p(r,t)}{\partial x^2} \tag{4}$$

$$E_x = \frac{E_0}{\varepsilon} e^{-\frac{x}{\delta}} e^{i\omega t} \tag{5}$$

Then we get

$$\frac{\partial p(r,t)}{\partial t} = \mu(r)\frac{E_0}{\varepsilon} e^{-\frac{r}{\delta}} Cos[\omega t + \varphi]\frac{\partial}{\partial r}[p(r,t)] + D(r)\frac{\partial^2 p(r,t)}{\partial r^2} \tag{6}$$

The first term is the drift term and second is the diffusion term. It is a diffusion equation with an additional first order derivative with respect to x. φ is the initial RF phase at the emission surface.

We obtain the total number of electrons concentrated in the layer by integrating the electron destiny distribution. Assuming that all the electron that reach the surface of crystal leave it because of NEA the emitted photocurrent is determined via the differentiation of the number of electrons in the crystal with time.

$$N(t) = \int_0^h p(x,t)dx \tag{7}$$

$$I(t) = \frac{\partial}{\partial t}N(t) = \frac{\partial}{\partial t}\int_0^h p(x,t)dx \tag{8}$$

To numerically solve the Equation (6), we used the initial conditions shown in the Table 1.

Table 1: GaAs Parameters

Laser absorb coeffiention (780 nm)	7000cm-1
Electron mobility	2000 cm^2/v.s [5]
Diffusion coeffiention	30cm2/s [5]
Thickness	100um
Frequency	1.3GHz
E_0	15MV/m
Permittivity	12.36
Resistivity in 4K	1.1E-2 ohm-cm
Permeability	12.4

In the RF gun, the drift dominates the electrons' movements. Applying the formulae (7) and (8), we find that the temporal response of the GaAs photocathode is in the hundreds of femtoseconds for a delta function laser pulse.

We show for the first time a subps electron bunch can be created from a GaAs cathode in an RF gun. The ultra-short time response of GaAs photocathode in the RF gun eliminates the bombardment and minimizes both the bunch energy spread and emittance. Another advantage is the bunch can be shaped by the laser pulse very easily to minimize the space charge effect.

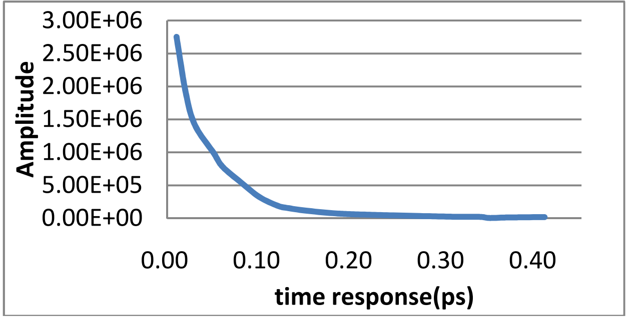

Figure 1: The bunch shape from GaAs is RF field responses to a delta function laser pulse.

MULTIPACTING STUDY

In order to understand the role of secondary emission in the decay of QE, a program was written to simulate the motion of a single electron in the gun and inside the GaAs crystal. It reads the field files from Superfish program. The initial secondary electron distribution data come from Monte Carlo simulation using CASINO[7], According to this simulation, if the primary electron trajectory is such that it returns back to the GaAs, its trajectory in the GaAs can be divided into three groups: most of the energy deposited close to the surface (Region I), most of the energy deposited in the middle of the GaAs (Region II) and most of the energy deposited near the back surface of the GaAs (Region III). The secondary electrons from Region I see a reduced or opposing RF field and hence are not emitted. The secondary electrons generated in Region III stay within GaAS for more than one RF cycle and hence oscillate back and forth within GaAs and are not emitted either. However, the secondary electrons generated in Region II can be emitted and can contribute to multipacting. Figure 2a describes the electron trajectory for this scenario, as a function of the RF phase and shows emission of the secondary electron from the GaAs. The location of this region within the GaAs is a strong function of the the RF field and RF phase at emission . Figure 3 illustrates the location of this Region II (section between the red and blue curves) within GaAs as a function of the RF phase for our 1.3 GHz gun operating at a field gradient of 15 MV/m. Since the laser pulse to be used for these experiments is ~ 10 ps, irradiating the cathode at the RF phase of 20 degrees to maintain low energy spread, the source for the secondary electrons is primarily the dark current from the cathode, emitted at random phases. Figure 3 indicates that at zero phase where the RF field and the dark currents are maximum, the region II lies 10-20 microns below the surface and could contribute to secondary electrons.

.

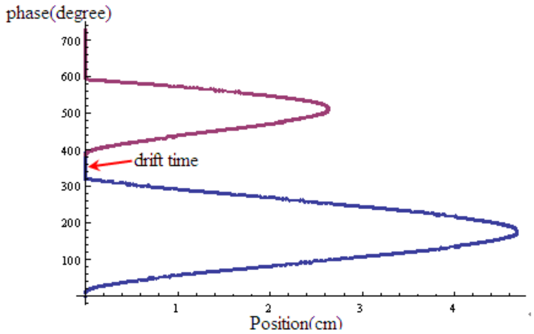

Figure 2: a) The curve depicts the trajectory an electron that has twice moved back to the gun. b) Electrons oscillate in the GaAs.

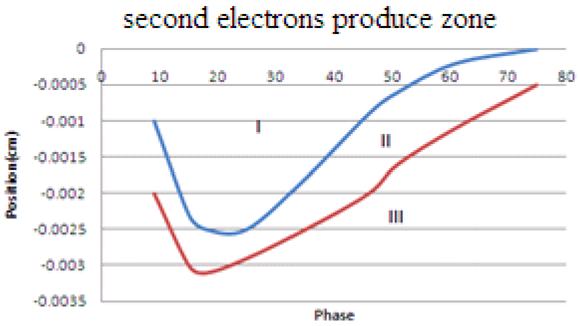

Figure 3: The secondary electron generate zone in GaAs.

CONCLUSION

The activity of our GaAs cathode is satisfactory at BNL. The next step will be to put the GaAs cathode into the gun, and carry out a beam load test. We estimated its temporal response of in the RF field. The tail of the bunch from the GaAs that is a critical factor in the performance of a DC gun can be ignored in the RF gun. Simulations of the multipacting effect reveals that the secondary electron emission yields which occur at different positions on the GaAs occasion different harmful effects on the Cs-O layer.

REFERENCES

[1] J. Kewisch et al., "The polarized SRF fun experiment", 18th International Spin Physics Symposium , Virginia, USA, Aug. 4, 2009.
[2] R. Xiang et al., "Low emittance polarized electron source based on superconducting RF gun", Proceedings of SRF2007, TUP66, Beijing, China.
[3] Private communication with Jörg Kewisch.
[4] P. Hartmann et al., Nucl. Instrum. Methods Phys. Res. A 379 (1996) 15.
[5] T. Nakanishi, "Polarized electron source using NEA-GaAs photocathode", Proceedings of Linac2002, Gyeongju, Korea.