EXPERIMENTAL STUDY OF GaAs PHOTOCATHODE PERFORMANCE IN RF GUN*

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Abstract

A prototype of S-band RF photogun with GaAs photocathode has been built and tested at Novosibirsk. The main goal of this prototype is to check a possibility of long time operation for GaAs photocathode in a strong accelerating field of RF cavity. The first experimental results concerning dark current and lifetime of GaAs photocathode in NEA condition under high RF power are presented. The dark current observed is much higher than predicted. Possible mechanism of large dark current emission from NEA surface is suggested and discussed.

1 INTRODUCTION

Nowadays GaAs polarized electron source is the best available because it has intrinsic advantages in performance of intensity, quantum efficiency, degree of polarization compared with other type of polarized electron sources. Combining all these advantages with a significant interest to polarized electron beams which comes from a high energy physics, we have chosen a GaAs photocathode for our RF photogun project. Unfortunately there was no experimental confirmation of possibility to use this cathode inside a cavity with high gradient accelerating field. In order to investigate a performance of GaAs photocathode in S-band RF gun the experimental bench was build in our laboratory. The detailed description of the installation can be found in [1].

2 EXPERIMENTAL RESULTS

2.1 GaAs photocathode with small quantum efficiency

The first experiments started in autumn of 1997 with the bulk GaAs cathode activated to quantum efficiency about $.01\% - .05\%$ on HeNe laser wavelength. It corresponds to positive electron affinity (PEA) state of a cathode. The aim of that run was to test all systems and measure cathode properties for different levels of RF power in the cavity. Dark current and lifetime were measured for the accelerating field strength up to $100 MV/m$. The detailed description of experiment and results can be found in [2]. In this experiment dark current after activation increased about two orders of magnitude. Measured dependence of dark current on cathode field strength was well in accordance with Fowler-Nordheim low. We observed decreasing of cathode lifetime from 200 min in absence of RF power to about 30 min in $30 MV/m$ accelerating field. This effect could be explained by vacuum worsening in the cavity due to dark current. After experiment we observed significant damage on the cathode surface.

2.2 GaAs photocathode with large quantum efficiency

New cathode was installed at the end of 1997. After 50 hours of baking at 300^oC pressure $2 \cdot 10^{-10}$ Torr was established. Only ion pumps were used at this stage. Cathode was activated following usual ”yo-yo” algorithm. Typical quantum efficiency on HeNe laser wavelength was $3\% - 5\%$ that ensures that cathode surface is in negative electron affinity (NEA) condition. Lifetime was 7-8 hours in activation chamber and practically the same in the cavity with RF switched off. Then cathode was moved to the cavity and RF power increased slowly step by step while dark current was controlled to prevent RF breakdowns causing cathode damages. Lifetime of a cathode in this case was just several seconds therefore we reduced repetition rate of RF pulses to .5 Hz. Signal from Faraday cup was measured by ADC and stored in computer after each RF pulse. Photocathode was moved to activation chamber after each 10-15 pulses for measurement of quantum efficiency. Typical record of experimental run is shown in Fig.1.

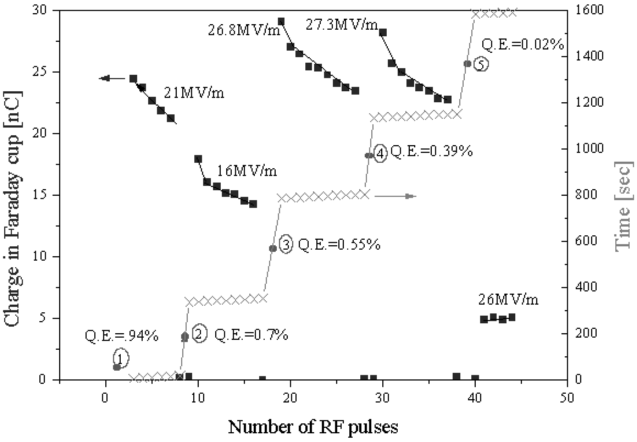

Figure 1: Dependence of charge in Faraday cup and quantum efficiency upon number of RF pulses

One can see from fig.1 that dark current depends on quantum efficiency of the cathode and on the strength of RF field. The dependence of dark current upon field strength on the cathode is shown in Fig.2 in Fowler-Nordheim (FN) coordinates.

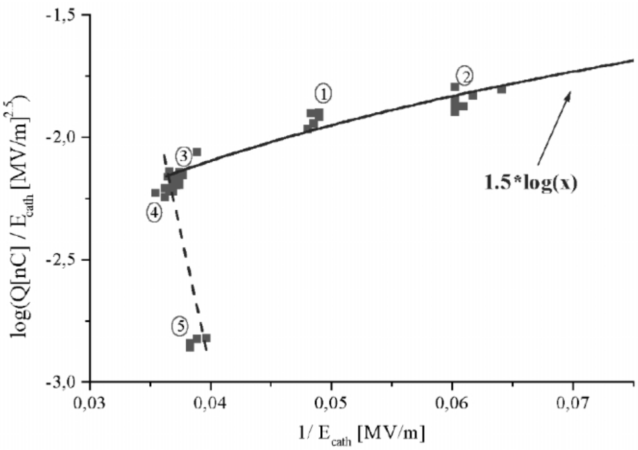

Figure 2: Fowler-Nordheim plot

In principle, Fowler-Nordheim low describes a field emission from a metal surface, however experimentally measured dark current from semiconductor PEA photocathode satisfies this low as well citetest,candela. It is not true in our case as seen from Fig. 2. Indeed, there are two branches: 4 -5 has normal negative slope and 1-3 has anomalous positive slope, which probably coincide to PEA and NEA regimes of the photocathode respectively. Indeed, a dark current dependence upon electric field strength can be described as:

$$I = I_0 \cdot (\beta E_C)^{2.5} \cdot exp(-\frac{\alpha\phi^{1.5}}{\beta E_C}), if \phi > 0$$

$$I = I_0 \cdot E_C^{\gamma}, if \phi \leq 0$$

Here E_C is field strength on the cathode, α, β are FN parameters, ϕ is cathode work function, γ is constant. In FN coordinates $x = 1/E_C$, $y = log(I/E_C^{2.5})$ this set of equations becomes:

$$y = \log(I_0\beta^{2.5} - \log e \cdot \frac{\alpha\phi^{1.5}}{\beta} \cdot x), if \phi > 0$$

$$y = \log I_0 + (2.5 - \gamma) \cdot \log x, if \phi \leq 0$$

It corresponds well to experimental points if $\gamma = 1.0$ as demonstrated by fitting curve in fig.2.

3 MECHANISM OF DARK CURRENT GENERATION

The observed dependence of dark current on electric field can be understood if one assume that free electrons present in conduction band of a photocathode even in absence of illuminating light. When work function is positive these electrons penetrate through a surface barrier in accordance with usual FN theory. In opposite case of NEA condition there is no barrier and electrons escape from a crystal immediately as they reach its surface resulting in weak dependence of current on strength of accelerating field. As we show below, back bombardment, inherent for RF gun operation, can be responsible for charge build up in a cathode in NEA state.

3.1 *Charge build-up Due to Back Bombardment*

Lets assume that there is some charge q_n in a conduction band of a cathode after n RF pulses, then electrons can travel to crystal surface and escape to vacuum with probability Y. After emission some electrons are accelerated to gun exit other returned back to the cathode with probability k_r depending on RF phase of electric field. Returned electrons can excite large number M of additional electrons from valence to conduction band. (It is well known that NEA semiconductors have very large secondary emission coefficient [4].) Again these new electrons may excite electrons after emission in proper RF phase providing rapid growth of charge inside a cathode. Charge after the next RF pulse can be found as:

$$q_{n+1} = q_n \cdot e^{\frac{-T}{\tau}} + (Y \cdot q_n) \cdot k_r \cdot M =$$

$$= qn \cdot (e^{\frac{-T}{\tau}} + Y \cdot k_r \cdot M) \approx q_n \cdot g \cdot k_r$$

Here q_n,q_{n+1} is a charge inside a cathode on a successive RF pulses, T is RF period, τ is electron lifetime in a bulk of a cathode, Y-quantum efficiency, k_r is back bombardment coefficient depending only on configuration of e/m fields and cavity geometry, M is multiplication factor, $g = YM$ is secondary emission coefficient depending on cathode properties only.

Solution of this equation is

$$q_n = q_0 \cdot (g \cdot k_r)^n \Longrightarrow q(t) \propto (g \cdot k_r)^{\frac{t}{T}}$$

One can see that charge inside crystal grows exponentially if $gk_r > 1$. Typical cathode parameters $Y \approx 005$, $M \approx 200 - 2000$, $k_r \approx .25$ give estimation for $gk_r \approx .25 - 2.5$. It is near a critical value providing that back bombardment can be responsible for dark current generation and even small variation of gk_r have to enhance or suppress dark current significantly.

Computer simulation of charge build up in a cathode was done using model of pillbox cavity. Typical result of this simulation for some values of secondary electron emission coefficient g is shown in fig.3. The maximum charge multiplication is observed on the edges of RF pulse where back bombardment coefficient is maximal.

4 CONCLUSIONS

The experimental results reported above allow making the following conclusions:

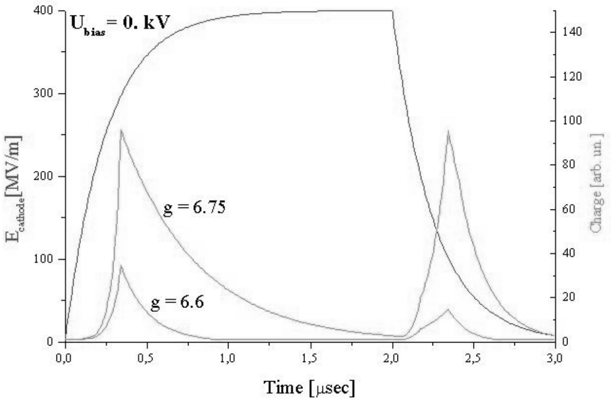

Figure 3: Build up of a charge in a cathode during RF pulse

GaAs photocathode can operate in a RF cavity with accelerating electric field strength up to $30MV/m$ without irreversible damages. After degradation due to bad vacuum conditions it can be activated again many times using standard procedure.

Dark current from an activated to NEA bulk GaAs photocathode exceeds by 2 - 3 orders of magnitude dark current of PEA photocathode in a field of the same strength.

The dependence of dark current from GaAs photocathode activated to quantum efficiency about 1% upon electric field strength doesn't satisfy Fowler-Nordheim low.

Back bombardment of a cathode in RF gun combined with large secondary electron emission from NEA surface can be responsible for emission of large dark current In this case reducing of back bombardment coefficient and (or) secondary emission coefficient can suppress dark current considerably. Non-uniform magnetic field and (or) low voltage cathode bias may be used for reduction of number of returned electrons. Reducing cathode thickness that is favorable also from the point of view of maximum achievable polarization can reduce secondary electron emission coefficient.

5 FUTURE DEVELOPMENTS

More experimental data are needed for further investigation dark current from GaAs photocathode in RF gun therefore we have made modernization of our installation.

The main problem for experiment is very short lifetime of activated cathode under high gradient RF field. We believe that reason is intense gas release in Faraday cup that is very close to the cathode location. Now distance from the cavity to Faraday cup is increased and additional pumping is placed between them. Differential pumping will separate vacuum near cathode from vacuum in Faraday cup chamber.

Wall current monitor with 100ps resolution is installed into beamline to observe a shape of dark current pulse. We can compare it with predictions of back bombardment model and check validity of this model.

A coil producing non-uniform magnetic field is installed near the gun cavity to reduce number of returned electrons. If back bombardment model is correct reducing number of returned electrons will lead to significant reduction of dark current.

6 ACKNOWLEDGEMENTS

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