A STUDY OF LIFETIME OF GaAs PHOTOCATHODE FOR HIGH BRIGHTNESS ELECTRON SOURCE

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Abstract

The Beam Physics Laboratory of Hiroshima University has studied GaAs photo-cathode for a high brightness electron source. It aims to develop a cathode with the higher quantum efficiency and longer-lifetime. The Negative Electron Affinity (NEA) surface is essential for GaAs to activate as an electron source. By artificial treatments, NEA surface is made on GaAs cathode, so that electron beam can be extracted to vacuum with a laser pulse, whose energy corresponds to the band gap. NEA surface is made by Yo-Yo method, alternating deposition of Cs and O_2 to a GaAs surface. In this article, we examine a lifetime of the GaAs cathode, as a function of temperature. We evaluated also a temperature rise on the cathode surface by laser, which generates the electron bunch train. Temperature rise depends on the laser spot size; it is 60K for 10mm. We observed a significant degradation on the lifetime by heating cathode. By considering expected temperature rise and this result, some active temperature control is necessary to obtain an enough operation lifetime for high brightness electron source, because of the small spot size (a few mm) and high power (several 10 W).

INTRODUCTION

There are several future accelerator projects based on linac, e.g. ILC (International Linear Collider) [1], Compact Linear Collider (CLIC), Energy Recovery Linac (ERL) [2], Free Electron Laser (FEL) [3], etc. In these accelerators, electron source is one of the most important components, which decides the total performance. So far, there are wide varieties of demands for electron source, e.g. low emittance, high current, short pulse, high quantum efficiency in case of photocathode, and long operational lifetime, polarization, etc. One of candidates is NEA GaAs cathode [4]. In spite of the high performance of the NEA GaAs cathode, operational lifetime is concerned. In this article, we studied the operational lifetime as a function of cathode temperature. In a real operation, a high power laser is illuminated on the cathode surface to make a high current electron beam. It is 15W for ERL case. In addition, the laser spot size is 1mm radius or less for extreme low emittance beam. In such case, the cathode surface is heated by the laser and a significant temperature rise is expected. If the operational lifetime is affected by this temperature rise, it is a big problem on these future projects. That is why we studied the effect of temperature on the GaAs cathode.

Temperature rise on the cathode was estimated with the following simple model as show in Fig. 1(a). A small circle plate represents the cathode spot area, which is connected to a slotted plate. This plate is attached to an end of a barrel cylinder, which represents the cathode support rod. Another end of the cylinder is thermally anchored. 15 W thermal flow is given at the cathode and the estimated temperature is plotted in Fig. 1(b) as a function of the cathode spot size.

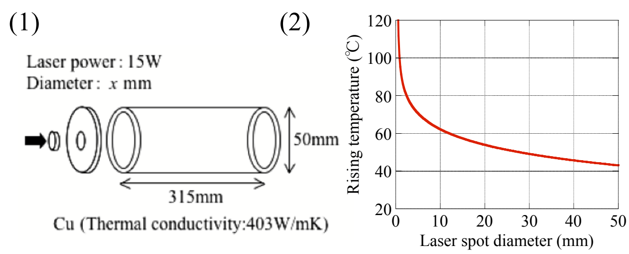

Figure 1: (a) A simple model for cathode and support rod. (b) Temperature rise as a function of the cathode size. 15W flow is given.

According to the result, more than 40K rise is expected with 50mm diameter and it becomes 80K with 2mm diameter. In the future accelerators, the laser spot size is from 2 mm (ERL and FEL) to 10mm (ILC) diameter. The lifetime degradation due to the temperature rise should be negligible, at least, reasonably small, for these cases.

PHOTO-CATHODE REST BENCH

The experiment was carried out with photo-cathode test bench at Hiroshima University. Figure 2 shows schematically the main chamber of the photo-cathode test bench. The chamber is made of SUS 316; the inner surface was finished by chemical polishing. The cathode is mounted at the end of a rod, which is electronically isolated from the main body by a ceramic insulator. The chamber is kept in ultra high vacuum (typically 9E-9Pa) with an ion pump (160l/s) and a NEG pump (310l/s).

GaAs is placed on the cathode bed, which is at the end of the rod and made from Mo. GaAs is fixed by Ta foil

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and is soldered by a paste for thermal conduction. The laser is irradiated from the view-port. The tungsten heater and thermocouple are equipped in the rod for the heat cleaning process. This heater is used for this study. Moreover, the Cs dispenser and the variable leak-valve for O_2 introduction, which are necessary for NEA activation, are also equipped.

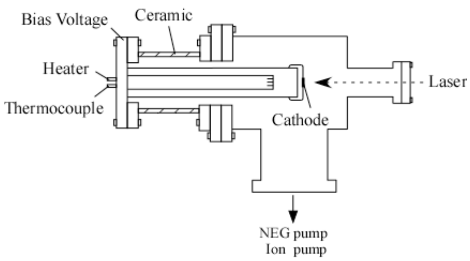

Figure 2: The cross section of the main chamber of photo-cathode test bench.

NEA-ACTIVATION

Zn doped bulk GaAs crystal (100) was used as a cathode material. The doping density is 4.0E+19/cm^3. This high doping causes the band bending on the surface, which lowers the work function effectively. 1-inch cathode wafer is cut to 4 pieces, and is etched by a solution of sulfuric acid and hydrogen peroxide. The GaAs piece is then rinsed by distilled water and further treated by a solution of hydrochloric acid iso-propanol. After these treatments, GaAs wafer is stored in a vacuum desiccator box to prevent developing oxide layer on its surface. GaAs wafer is then set on the cathode bed. After the vacuum chamber is closed, usual vacuum baking process is done to establish ultra high vacuum. NEG activation is also performed at the last of the baking process.

Once ultra-high vacuum is established (typically 1E-8Pa or less), heat cleaning is done. The cathode bed was heated with the tungsten heater for one hour at 550℃. The temperature was monitored by not only the thermocouple, but also radiation thermo-meter. When the cathode temperature returned to the room temperature, the NEA activation and the lifetime measurement were performed. During the measurement, -100V bias voltage was applied to the cathode bed. He-Ne laser (633nm) is irradiated from the view-port in front of the cathode to make photo-electron emission. The laser power was in rage of 5 to 40μW. The spot size in cathode was 293μm and 286μm in x and y axes, respectively.

The NEA activation was done with a conventional Yo-Yo method. Cs and O_2 were alternately evaporated on the cathode. The emission current from the cathode was monitored to confirm the progress of the NEA activation. A typical vacuum pressure during the activation process were 1.0E-7Pa and up to 1.6E-6Pa for O_2 and Cs, respectively. Time evolution of photo-current (Quantum Efficiency, QE) is shown in Fig. 3. QE is progressively increased up to more than 10%.

To study thermal property of cathode performance, the cathode is heated by the tungsten heater, which is originally equipped for the heat cleaning process. The cathode temperature was monitored with the thermocouple. When we turned on the tungsten heater, cathode temperature gradually increased up to 110℃ and 140℃, with heater voltage of 15 V and 20 V, respectively.

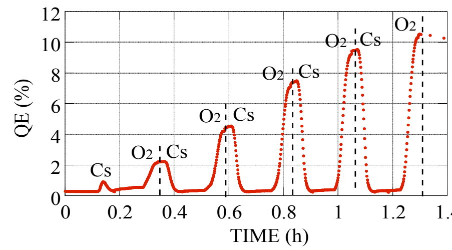

Figure 3: An example of NEA activation by Yo-Yo method.

RESULT AND DISCUSSION

Results of QE and lifetime measurement of the heated cathode is shown in Fig. 4(a) and (b), respectively. Laser power was fixed at 20μW during the measurement. The lifetime was extracted from the QE curve for each 0.4 hour period by fitting with the expression of

$$\mathrm{QE} = \mathrm{QE}_0 \exp\left(-\frac{t}{\tau}\right). \qquad (1)$$

where, QE_0 is the initial value of QE, τ is lifetime.

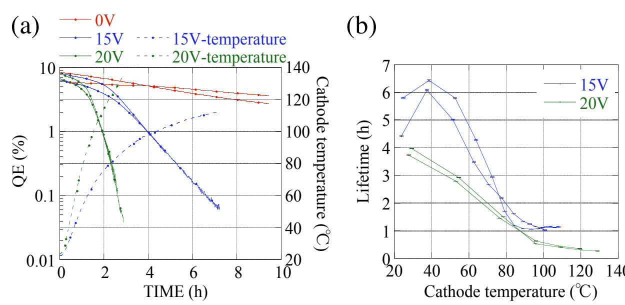

Figure 4: (a) QE and temperature time evolution, and (b) lifetime as a function of temperature.

According to the results, QE was decreased significantly as cathode temperature went high, comparing QE curve of 0V (no heating) in Fig. 4(a). The lifetime was also significantly decreased at 60K or higher temperature rise as shown in Fig. 4(b). The deterioration of the vacuum level because of the cathode heating was not seen. The lifetimes of 0V of two measurements is 8 and 20 hour each.

A Lifetime can be separated into two components, which are a dark lifetime and a beam lifetime. Dark lifetime is the decay time constant of QE, which is regardless of the extracted charge amount. On the other hand, the beam lifetime is defined as a decay constant of QE regarding the extracted charge amount. QE is formalized with these two constants as follows,

$$\mathrm{QE} = \mathrm{QE}_0 \exp\left(-\frac{t}{\tau_d}\right)\cdot \exp\left(-\frac{\int I_{(t)}dt}{Q}\right), \qquad (2)$$

where τ_d is the dark lifetime, $I_{(t)}$ is emission current, and Q is the beam lifetime.

Dark lifetime was measured with low average τ_d current (0.48-30nA/s), so that QE decay due to the beam lifetime was negligible. The dark lifetime was found to be 118hours at room temperature.

The beam lifetime was extracted from several QE decay curves with different laser power as follows. Assuming the emission current I is constant during the lifetime measurement, QE evolution in time is expressed as,

$$\mathrm{QE} = \mathrm{QE}_0 \exp\left\{-t\left(\frac{1}{\tau_d} + \frac{I}{Q}\right)\right\} = \mathrm{QE}_0 \exp\left(-\frac{t}{\tau}\right) \quad (3)$$

$$\frac{1}{\tau} = \frac{1}{\tau_d} + \frac{I}{Q}. \quad (4)$$

τ is the lifetime, which is directly extracted from QE decay curve. Figure 5(a) shows decay curves of emission current with various laser power conditions. By plotting $1/\tau$ as a function of emission current, the beam lifetime Q is extracted as inverse of gradient of the fit line as shown in Fig. 5(b). Q was estimated to be 0.12[C] from these data. If we normalized this beam life with its emission area, it was 46.0[C/cm^2] wtih laser profile of σ_x=293μm and σ_y=286μm at room temperature.

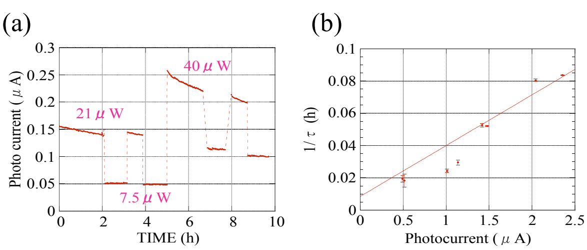

Figure 5: To extract beam lifetime at room temperature, photo-current with various laser power conditions are measured (a). $1/\tau$ is plotted in (b) as function of photo-current.

Same measurements were made by heating the cathode. Dark lifetime was measured with 0.7μW laser power, where emission decay due to beam lifetime is negligible. Moreover, to extract beam lifetime, QE decay curves were measured with various laser power (7μW, 20μW, 40μW). These lifetime evolutions are shown in Fig. 6 (a). Figure 6 (b) shows the lifetime as a function of cathode temperature. Curves with four different laser power conditions (emission current) are almost overlapped and there is no significant difference. It means that the measured lifetime is dominated by dark lifetime, τ_d, and our measurements do not have any sensitivity on the beam lifetime. So far, when the cathode is heated, the beam lifetime is much longer than the dark lifetime, but we do not know the exact number. Other word, the dark lifetime is significantly affected (shortened) when the cathode is heated, and simply decreased as temperature goes high as shown in Fig. 6(b).

As a conclusion, the cathode lifetime of NEA bulk GaAs is strongly influenced by the temperature. The lifetime is simply decreased for higher temperature. The variation is dominated by the dark lifetime and deviation on the beam lifetime due to the cathode temperature is not extracted from our data. Considering high brightness electron source such as ERL injector, the lifetime decline due to the cathode temperature is going to be one of the biggest issue, because the estimated temperature rise is more than 50K with 20mm or less spot size. In our case, the lifetime is only 2 hour at 75°C (50K temperature rise). It is hard to control the cathode temperature by enlarging the laser spot diameter according to the model calculation as shown in Fig. 1(b). Therefore, an active cooling system to suppress the temperature rise is necessary for this type of cathode.

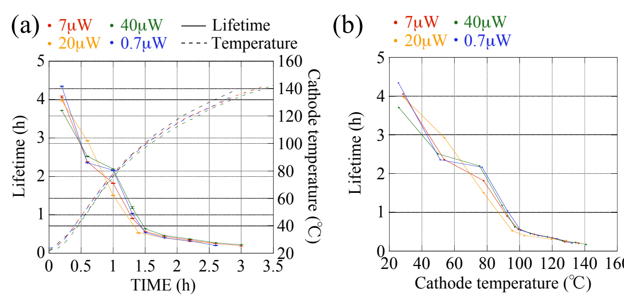

Figure 6: Lifetime (and Dark lifetime: 0.7μW) is measured by heating cathode. Data are taken with four laser power conditions. Lifetime (a) as function of time (b) as a function of cathode temperature, are shown.

FUTURE

More systematic study should be made. At first, we should improve the lifetime to get better sensitivity on the measurement. It is also technically important by considering the actual operation of such high brightness electron gun. Once the extremely high vacuum is established, effects of the vacuum can be studied. We are also planning to perform the surface analysis with Auger spectroscopy, and examine the deterioration process on the NEA surface.

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