INITIAL EMITTANCE AND TEMPORAL RESPONSE MEASUREMENT FOR GaAs BASED PHOTOCATHODES*

S. Matsuba#, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki, Japan
(Graduate School of Science, Hiroshima University, Higashihiroshima, Hiroshima, Japan)
Y. Honda, T. Miyajima, T Uchiyama, M Yamamoto,
High Energy Research Organization (KEK), Tsukuba, Ibaraki, Japan
X.G. Jin[1,2], Y. Takeda[2], [1]Institute for Advanced Research, Nagoya University, Nagoya, Aichi, Japan
[2]Department of Crystalline Materials Science, Graduate School of Engineering, Nagoya University, Nagoya, Aichi, Japan

Abstract

For future light source based on Energy Recovery Linac (ERL) is planned in KEK. For the ERL, an ultra low emittance, fast temporal response and high current electron source is needed. To achieve these requirements, a high voltage DC gun with a Negative Electron Affinity photo-cathode is under development. In this development, it is important to investigate the performance of photo-cathodes. We have constructed an ERL gun test stand to measure emittance and temporal profile. We use a solenoid scan technique for emittance measurements and a deflecting cavity technique for temporal profile measurements. In this presentation, we report KEK ERL gun test stand and beam test results.

INTRODUCTION

NEA GaAs photocathode with DC gun is one of candidate for an electron source of the ERL based next generation light source. In KEK, for the purpose of development for ERL based light source the Compact ERL is constructing [1]. The achievable emittance and duration of pulse of the electron beam from a DC photoemission gun are limited by the initial emittance that depends on Mean Transverse Energy (MTE) of electrons and temporal response of photo cathodes, respectively. To clarify these performances of the GaAs photocathode, we prepared the cathodes with different thicknesses, and measured the emittance and the time response. In this paper, we reported the results of the experiments.

EXPERIMENTAL SETUP

Photocathodes

Photocathodes were fabricated by Metal Organic Vapor Phase Epitaxy at Nagoya University. Figure 1 shows the schematic structures of the cathodes. The cathode samples can be divided two types by a substrate material. One of substrate was AlGaAs, and the active layers of cathodes were 100 nm, 300 nm, and 1000 nm thick. Another was intrinsic GaAs, and the active layers of cathodes were 300 nm and 1000 nm thick. An electron inside the cathode can't penetrate the layer of AlGaAs, because energy band of AlGaAs are wider than p-doped GaAs. On the other hand, the substrate of intrinsic GaAs have smaller band gap, and electron can penetrate toward the substrate. Since emitted electrons which is reflected by substrate are take more time for emission than electrons which is not reflected. These boundary conditions affect the temporal response of the cathode . We call boundary conditions of AlGaAs and intrinsic GaAs, "wall" and "valley" type bound respectively. The Zn doping concentration of the active layer was controlled to be 1.5×10^{-18} cm^{-3}. The doping concentration was increased to 6×10^{-19}cm^{-3} at the 5-nm heavily-Zn-doped GaAs surface layer as shown in Fig. 1.

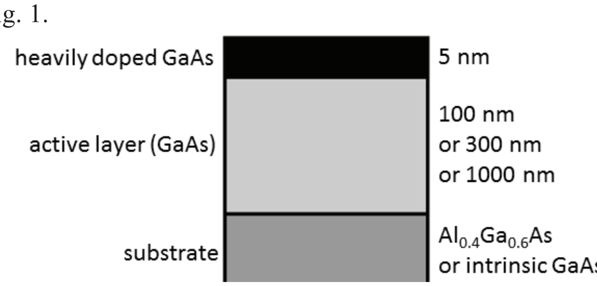

Figure 1: Crystal structure of thickness controlled photocathodes.

The DC electron gun was originally developed as a polarized electron source for the International Linear Collider, and the maximum voltage is 200 kV. A schematic drawing of the beamline is shown in Figure 2.

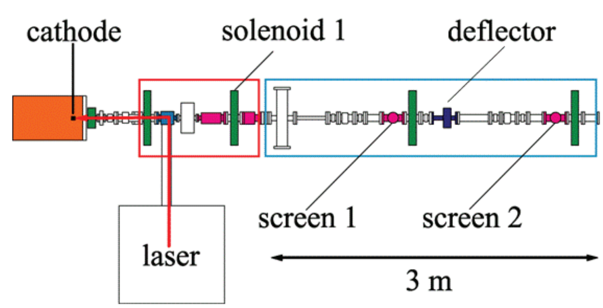

Figure 2: Schematic drawing of gun test beamline.

The beam profile was measured by an aluminum-coated Ce:YAG screen monitor. The optical profile of the screen was observed with an 8-bit charge-coupled device (CCD) camera. The solenoid magnet (solenoid 1), which was placed in a position 1.5 m from the cathode, was used in the waist scan. Waist scan are excecuted by soleonoid magnet and two screens. We averaged the emittance value of two screens. Time response measurements were carried out by using a deflecting cavity [2]. The cavity is installed in 1 m upsteam from screen 2 which was used to measure profile of deflected beam. The bunch is given time dependent kick to the transverse direction by radio frequency (RF) field. RF frequency of deflecting cavity is 2.6 GHz. The time structure of a bunch is projected on a screen after the cavity.

EMITTANCE MEASUREMENT

Theory

On the surface of photocathode, the normalized rms emittance is expressed by following equation,

$$\epsilon_{\mathrm{nrms}} = \frac{1}{m_e c}\sqrt{\langle x^2\rangle\langle p_x^2\rangle} = \sigma_x\sqrt{\frac{2\langle E_{k_x}\rangle}{m_e c^2}}.$$

Here the transverse electron position is given by x, x' is the electron divergence, p_x is the momentum, m_e is the rest mass of the electron, and c is the speed of light. The brackets represent the ensemble average of all particles. $\langle E_{k_x}\rangle$ is called Mean Transverse Energy (MTE). The performance of photocathodes is well described by MTE. We transferred the emittance to MTE.

Simply, MTE depend on excited energy by laser and energy loss before emission. Inside photocathodes, an electron is scattered by phonon, and loose energy. Finally the energy of electrons is achieved till the thermal energy at room temperature. The scattering rate is increased with electron transport distance in the photocathodes.

Therefore, we measure the thickness dependence of MTE.

Laser System and Beam Condition

We used a He-Ne laser and a semiconductor laser for the emittance measurements. The operating wavelengths for He-Ne laser and the semiconductor laser are 544 nm and 785 nm. The distributions of lasers on the cathodes are adjusted to central part of Gaussian by a circular aperture pinhole and lenses.

Results

Figure 3 shows a typical result of the measured emittance for two different laser spot diameters. To obtain the MTE, these results were fitted to a line that intersects the origin.

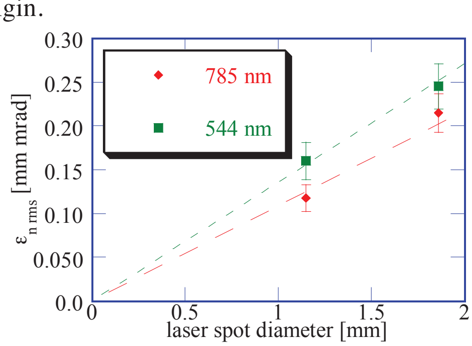

Figure 3: Typical emittance measuremts result with various spot size of irradiated laser on surface of cathodes.

Figure 4 shows the measured MTEs of all the cathodes at laser wavelengths of 544 and 785 nm. No clear thickness dependence of the MTEs was seen within the error bounds. I apologize that there were some mistakes in the data in the reference [3]. Therefore I collected the data of MTE. Figure 1 shows the MTE of some cathodes. MTE don't depend on the active layer thickness in the range of error. Green line is the thermal energy at room temperature.

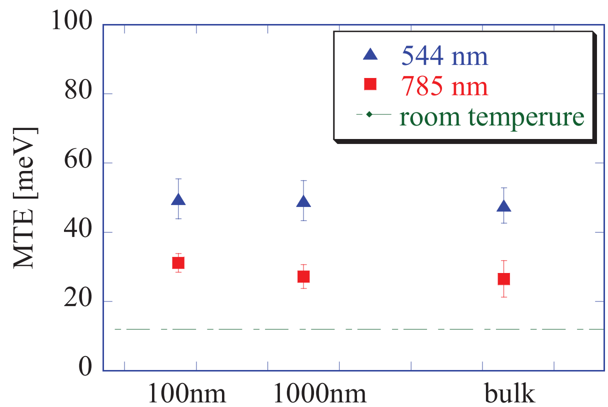

Figure 4: Results of MTE.

TIME RESPONSE MEASUREMENT

Theory

Electron emission is explained by three step model [4]. In this model, distribution of excited electrons in the cathode is evolved by diffusion. The model is well explained the experiment results.

Laser System and Beam Condition

For temporal response measurements, the mode locked Ti-Sa laser was used. The pulse repetition frequency is 81.25 MHz (1/16 of 1.3 GHz). The pulse widths of the lasers are measured about 2~3 psec by autocorrelator. The measurements were carried out at the laser wave length of 850 nm.

Results

Figure 5 shows typical images of time response measurements. The data show the temporal structure of the beam. The right side of the beam profile corresponds to the head of the bunch, and left side is tail part of the bunch. The intensity of the data are projected and integrated on the transverse axis of the ccd image. The projected intensity are shown in red and blue dot of Figure 6. As shown in Figure 6, the pulse duration of beam are wider than 100 psec range that is about a quarter of a period of RF frequency of deflecting cavity. The beam delayed more than 100 psec from bunch head, were overlapped to the beam arrived early on screen. To solve the problem, we assume the function of temporal response and analyse the data.

Assumed function $S(t)$ is the defined by

$$S(t) = S_s(t) + S_f(t),$$

ISBN 978-3-95450-115-1

$$S_{f,s}(t) = \frac{A_{f.s}}{2\tau_{f.s}^2}\exp\left(\frac{\sigma_t^2}{2\tau_{f.s}^2}\right)\cdot\exp\left(-\frac{t-t_0}{\tau_{f.s}}\right)\cdot erfc\left(\frac{\sigma_t}{\sqrt{2}\tau_{f.s}}-\frac{t-t_0}{\sqrt{2}\sigma_t}\right).$$

This means $S_f(t)$ and $S_s(t)$ is the same form. And, $S_f(t)$ used A_f and τ_f , $S_s(t)$ used A_s and τ_s . $S_f(t)$. $A_f, \tau_f, A_s, \tau_s, t_0, and\ \sigma_t$ of six parameters are obtained by fitting data points. The parameters of function are determined by a fitting to minimize the square of the difference between the function and the measurement data. The function are well reproduced the measurement data. Therefore, we show the fitting results as the measured time response.

Figure 7 shows measured temporal responses of cathodes. The cathodes of 1000 nm thickness with wall type boundary have slowest response. Next slower is the bulk GaAs. And valley 1000 nm, wall 300 nm, valley 300 nm, and wall 100 nm follow bulk GaAs. The results shows that the temporal response become slower when the thickness becomes thicker, and boundary condition become wall type.

Figure 5: Typical CCD image of temporal response measurements.

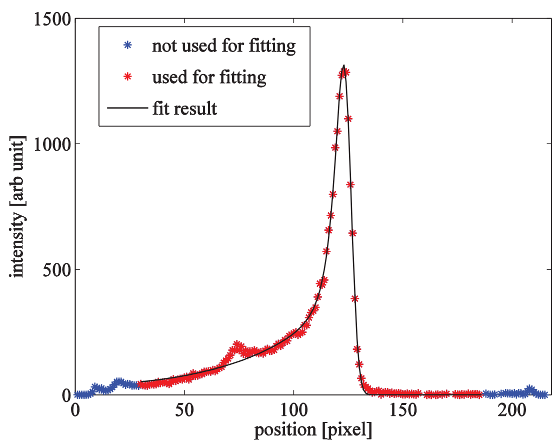

Figure 6: Integrated intensity projected onto the transverse axis of Fig. 5.

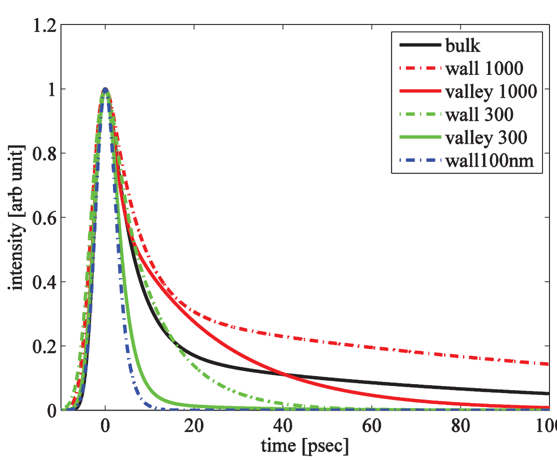

Figure 7: Estimated temporal response function of all cathodes.

DISCUSSION

Emittance Measurement

From the results of the MTE, the dependence of thickness is not observed in the range of error. Since many electrons have same energy, thermalization of electrons was roughly completed. But, MTE is not decreased till the thermal energy at room temperature. We think the rough surface cause the increase of MTE. The surface roughnesses of the photocathodes were measured by the atomic force microscopy. The surface roughness of thickness controlled cathode was about rms 7 nm. The roughness can explain the measured MTE.

Time Response Measurement

Considering the diffusion model, it is expected that the boundary of wall type has a slower response. Our results don't have fatal difference. We solved the diffusion equation to reproduce experimental results. Figure 1 show ~ the diffusion constant adjusted 35cm^2/s. However, this is a half of the ref 4. We are considering the reason of the difference. Apart from this, the temporal response are well described diffusion model.

CONCLUSION

We measured the initial emittance and temporal response with various thicknesses of GaAs active layer using waist scan and deflecting cavity respectively. The emittance doesn't depend on thickness of active layer in the range of error bound. The temporal response depends on the thickness of active layer and substrate material, and the diffusion model roughly agreed. To obtain a lower emittance, photocathodes which have smooth surface are candidate. Temporal response are adjusted by control the thickness of active layer and substrate material. These results contribute the design of photocathodes.

ACKNOWLEDGEMENT

This work was supported in part by a Grant-in-Aid for Scientific Research (A) 23246003 from the Japan Society for the Promotion of Science, and by research funds from the KEK Cooperative and Supporting Program for Research and Education in Universities.

REFERENCES

[1] S. Sakanaka et al., MOPPP018, these proceedings.

[2] S. Matsuba et al., Proc. 1st IPAC. Kyoto, 2010, p. 2335.

[3] S. Matsuba et al., Jpn. J. Appl. Phys. 51(2012) 04602.

[4] W. E Spicer and A. Herrera-Gómez, SLAC-Publication No. 6306 (1993).