A STUDY OF LIFETIME OF NEA-GaAs PHOTOCATHODE AT VARIOUS TEMPERATURES*

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Abstract

We report that a thermal property of GaAs photocathode activated the surface to negative electron affinity (NEA) at various temperatures. An electron source with the NEA-GaAs photocathode is an important device for high-average-current electron accelerators, such as a next-generation light source based on an energy recovery linac, in which a high power laser is illuminated to the photocathode for generation of the electron beam of 100mA. Consequently the high power laser causes to rise the GaAs temperature. The degradation of photo emission from the cathode is enhanced by a thermal desorption of Cs/O adlayer due to the temperature rise, even if the beam is not extracted. We have measured the cathode lifetime at various temperatures to evaluate the thermal property of the NEA surface.

INTRODUCTION

An electron source of a negative electron affinity (NEA) GaAs photocathode activated by means of a deposition of cesium (Cs) and oxygen (O_2) is an important device for electron accelerators. A DC electron gun with the NEA-GaAs cathode is used for high energy electron accelerators, such as a next-generation light source based on an energy recovery linac (ERL). A long operational lifetime of the cathode as well as a high-average-current of 100 mA and an ultra-small-emittance of 0.1 mm-mrad of the electron beam is desirable for ERL. Although the DC gun with the NEA GaAs photocathode is being developing in many laboratories, little attention has been paid to degradation of photo emission due to a cathode temperature rise. In a real operation, a high power laser (15W for 1% of the quantum efficiency [1]) should be illuminated on the cathode surface to generate the 100-mA of the electron beam. Therefore, the cathode surface is heated by the laser, and a significant temperature rise is expected. The degradation of photo emission from the cathode is enhanced by a thermal desorption of Cs/O due to the temperature rise, even if the beam is not extracted from the cathode.

In our previous studies, the temperature rise of 50 K was estimated by a simple model consisting of a GaAs wafer, a cathode bed and a cathode holder, considering their thermal conductance [2]. In addition, the efficient degradation of the lifetime at high temperature was obtained by means of $1/\tau$ lifetime analysis [2, 3].

However, variations of the lifetime appeared in our experiments because of the short measurement time and fluctuations of cathode temperature and vacuum pressure during the measurements. In this study, we have investigated the thermal property of the NEA surface by measuring the lifetime at various temperatures in a measurement of long duration and stable temperature and vacuum pressure.

EXPERIMENTS

The experiment was carried out by using of the simple system at Hiroshima University [2, 3] as shown in Fig. 1. A heat cleaning of the cathode surface, the NEA activation and lifetime measurements are performed in the same chamber kept in ultra-high vacuum (typically 5×10^{-9} Pa) with an ion pump (160 l/s) and a NEG pump (310 l/s). The GaAs wafer is mounted on a molybdenum (Mo) plate and held by a tantalum cap. The Mo plate is covered by a stainless steel electrode which is supported by a stainless steel rod and electronically isolated from the main chamber by a ceramic insulator. The Cs dispenser (SAES Getters) and a variable leak-valve (ULVAC) for O_2 introduction for the NEA activation are also equipped.
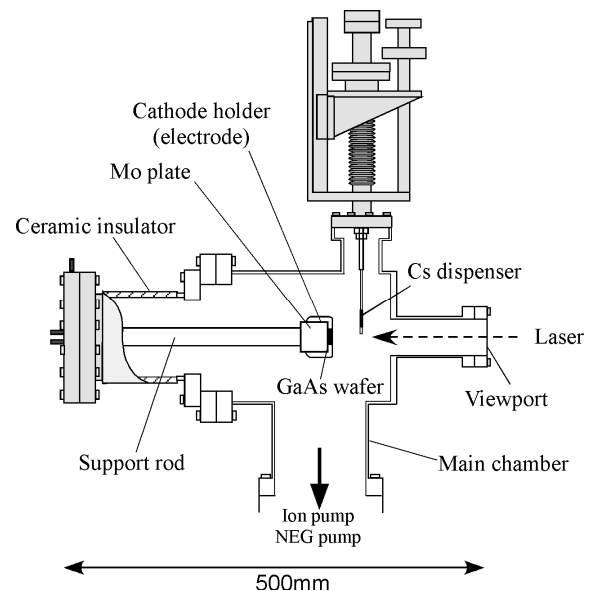

Figure 1: A schematic view of the experimental system. A heat cleaning, the NEA activation and the lifetime measuremets is performed in a main chamber.

The *p*-type GaAs(100) wafer is Zn-doped to 4.0×10^{19}/cm^3 and bulk crystal produced by Sumitomo Electric. The GaAs wafer was chemically etched [4].

The heat cleaning (550°C, 1 hour) is carried out by using of a cartridge heater at the back of the Mo plate. The heater is also used to control the cathode temperature during the lifetime measurement. The thermocouple, by which the GaAs temperature is monitored during the heat cleaning and the lifetime measurements, is attached to the Mo plate.

The NEA activation is achieved by means of a so-called "yo-yo" method where Cs deposition and O$_2$ exposure are alternately repeated several times. The typical quantum efficiency (QE) after the NEA activation is achieved to be approximately 10 %. The cathode is continuously illuminated by a He-Ne laser with wavelength of 633 nm, which introduces through a view port in front of the cathode holder. The holder is biased with a voltage of -100 V to accelerate the electron emitted from the GaAs surface.
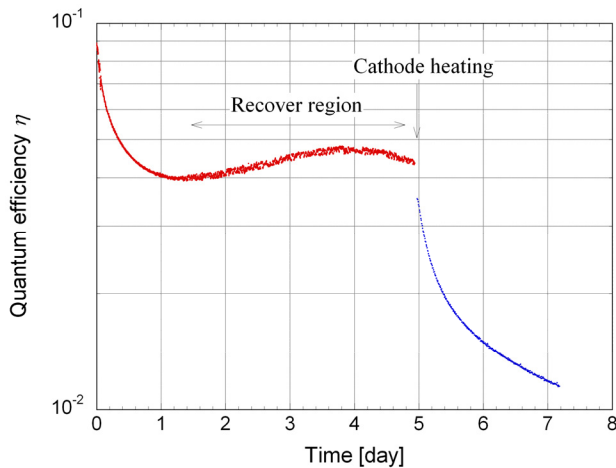

Figure 2: A typical decay curve after the NEA activation (red points) and the lifetime measurement at *T*=58.6 °C (blue points).

Figure 2 shows a typical decay curve after the NEA activation. The QE collapses down to 4 % within a day, after then recovers up to 5 % within a few of days, as shown in Fig.2 (red points). The cathode heating begins after the recover region. The laser power and illumination period are 40-80 µW and 1 sec at interval of 10 min, respectively. The illumination interval is controlled by a laser shutter. In the experiments, the low-current electron beam is extracted; the effect of beam extraction for the lifetime can be ignored. We refer to the lifetime as "dark lifetime". The experiment procedure of the heat cleaning, the NEA activation, and the lifetime measurement was repeated for each cathode temperature.

RESULTS

Figure 3 shows a series of decay curves in a logarithmic scale at the cathode temperatures of 22.8,

58.6, 71.9, 80.7 and 84.5 °C under the vacuum pressure of 5.4×10^{-9} Pa. The accuracy of temperature and vacuum pressure were ±0.4 °C and ±0.2×10^{-9} Pa respectively, which was mainly caused by the seasonal variation of environmental temperature. The difference of the vacuum pressure for each temperature was almost equal to the accuracy of vacuum during the measurement. At the room temperature (22.8 °C), the degradation of QE is dominantly caused by the adsorption of residual gasses to the NEA surface [5, 6]. A fit to the curve at *T*=22.8 °C in the form

$$\eta(t) = \eta_0 e^{-t/\tau} ,\qquad(1)$$

where η_0 is the initial QE and τ is the lifetime, gives τ = 203 hour. The result is consistent with our previous measurements [2, 3].
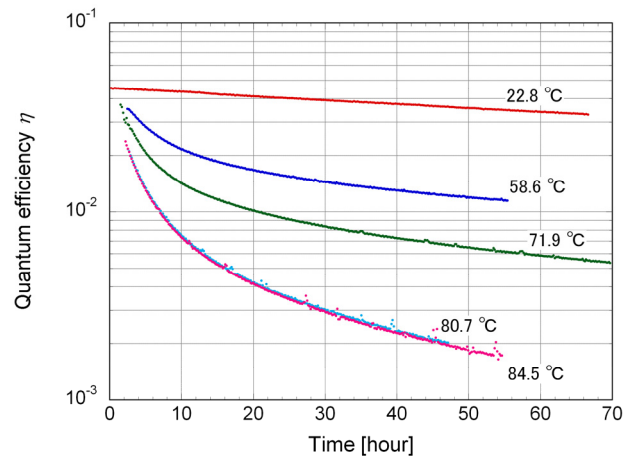

Figure 3: A series of decay curves at the various cathode temperature.

In the high-temperature regime, the degradation of QE is dominantly caused by the thermal desorption of Cs/O adlayer [3]. To analyze the decay curves, we have taken the thermal desorption effect into the fitting function. A reaction rate of thermal desorption is given by the Polanyi-Wigner's equation expressed as

$$\frac{d\theta}{dt} = -\upsilon_n \theta^n e^{-\frac{E_a}{RT}} = -k_n \theta^n ,\qquad(2)$$

where θ is the surface coverage of Cs/O, υ_n is the frequency factor, *Ea* is the activation energy, *R* is gas constant, *T* is the cathode temperature, and *n* is the order of the chemical reaction. We assume that the QE is proportional to the surface coverage. Thus, the η is given by

$$\eta = \gamma\theta ,\qquad(3)$$

where γ is a coefficient. Consequently the derivative of QE is derived as

$$\frac{d\eta}{dt} = -\gamma^{1-n}k_n\eta^n, \qquad (4)$$

and the time evolution of QE is given by

$$\eta(t) = \left\{\eta_0^{1-n} - (1-n)\gamma^{1-n}k_nt\right\}^{1/1-n}. \qquad (5)$$

The fit of the curve at T=84.5 °C to Eq. (5) is shown in Fig. 4. The reduced χ^2 value for the fit of the theoretical curve to the experimental curve is 1.9×10^{-6}, and the order of chemical reaction n is 2.1. The fitting results for each temperature are summarized in Tab. 1. The fits to the experimental curves are consistent with the thermal desorption model (Eq. (5)) in each temperature.
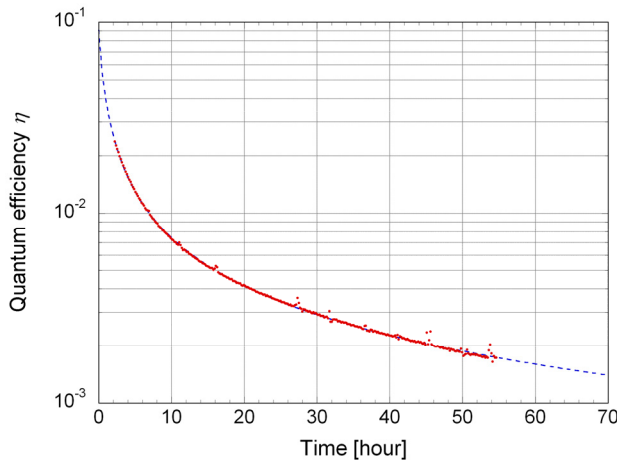

Figure 4: The experimental data at T=84.5 °C (red points) and the fitted curve (blue dash line).

Table 1: Fitting results of the chemical reaction order and the reduced χ^2.

Temperature T	Order n	Reduced χ^2
58.6 °C	3.7	6.4×10^{-6}
71.9 °C	3.0	1.8×10^{-5}
80.7 °C	2.1	1.6×10^{-6}
84.5 °C	2.1	1.9×10^{-6}

DISCUSSION

The quantity of n=2.1 obtained as the fit of thermal desorption model, i.e. Eq. (5), at T = 80.7 and 84.5 °C indicates that Cs desorbed from the NEA surface is combined with other adatoms (for instance O_2 or CO_2) on the surface to cesium oxide or cesium carbonate. However, the reason for the large values of the order of reaction n at T=58.6 and 71.9 °C is not clear at this moment. The consideration that the reaction order n is continuously decreasing with increasing the temperature

may be unsuitable. A possible interpretation of these results is that the relation between the QE and the surface coverage depends on the temperature.

Topping model [7, 8], which represents a relation between the change in surface work function ($\Delta\phi$) and the surface coverage, is expressed as

$$\Delta\phi = \mu\sigma\theta\left\{1 + 9\alpha(\sigma\theta)^{3/2}\right\}^{-1}, \qquad (6)$$

where σ is the number of dipole moment per unit area at $\theta = 1$, μ is the dipole moment and α is the effective polarizability. The linear term in Eq. (6) corresponding to Eq. (3) takes into account only the adsorbate-substrate interaction (Cs-Ga). The second term describes the depolarization due to the dipole-dipole interaction between the adatoms (Cs-Cs). The polarizability is proportional to the inverse of temperature T.

In the high-temperature regime, the change of work function is proportional to the surface coverage, since the second term can be ignore due to the polarizability decreasing with increasing the temperature. Hence the Eq. (3) is consistent with Eq. (6), assuming that the η is proportional to the $\Delta\phi$.

In the low-temperature regime, Topping's equation contains higher order, however the depolarization effect is not considered in term of Eq. (3). Therefore the depolarization effect may appear into the experimental curves at T=58.6 and 76.9 °C, as the reaction order n enlarges.

SUMMARY

The degradation of quantum efficiency at the temperature between 20 and 90 °C has been measured to evaluate the thermal property of the NEA surface. The fit of an equation considered Polanyi-Wigner model to experimental data at high-temperature is in good agreement. From the fitting results, the thermal desorption of Cs adlayer may occur following the second order of chemical reaction in high-temperature regime.

REFERENCES

[1] KEK Report No. 2007-7/JAEA Research 2008-032 (2008) (in Japanese), edited by R. Hajima, N. Nakamura, S. Sakanaka, and Y. Kobayashi.

[2] C. Shonaka, et al., Proc. of Particle Accelerator Conference (PAC09), MO6RFP069, 2009.

[3] M. Kuriki, et al., Nucl. Instrum. Methods Phys. Res. A, (in press)

[4] O. E. Tereshchenko, et al., Appl. Surf. Sci., 142(1999)75.

[5] T. Wada, et al., Jap. Jour. Appl. Phys., 29(1990)2087.

[6] D. Durek, et al., Appl. Surf. Sci., 143(1999)319.

[7] J. Topping, Proc. Roy. Soc. London Ser. A114(1927)67.

[8] A. R. Miller, Math. Proc. Cambridge Philosophical Soc. 42(1946)292