Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan
July 31 - August 3, 2019, Kyoto, Japan

PASJ2019 FROH04

NEGATIVE ELECTRON AFFINITY GAAS CATHODE ACTIVATION WITH CSKTE THIN FILM

M. Kuriki*, K. Masaki, Hiroshima University, Higashihiroshima, Japan

Abstract

Negative Electron Affinity (NEA) GaAs cathode is an unique device which can generate a highly polarized electron beam with circularly polarized light. The NEA surface which is necessary for spin polarization, is conventionally made by Cs and O/NF$_3$ adsorption on the cleaned p-doped GaAs crystal, but the robustness of the cathode is very limited, so that the electron emission is easily lost by residual gas adsorption, ion back-bombardment, etc. To improve the cathode robustness, NEA activation with a stable thin-film on GaAs surface according to Hetero junction hypothesis has been proposed by the author. An experiment of the NEA activation with CsKTe thin film was carried out at Hiroshima University and a significant electron emission with 1.43 eV photon was observed which strongly suggested NEA activation. The cathode showed 16 to 20 times improvement of lifetime comparing to GaAs activated with Cs and O.

INTRODUCTION

Spin is one of the fundamental quantum number of electron and sensitive to magnetic structure of material. Spin polarization is then important to define the state in the nuclear and particle physics and observe the magnetic structure in material sciences. Spin polarized electron beam has important roles in ILC (International Linear Collider) which is the next project of high energy physics; By suppressing the background events and improving the effective luminosity, it increases the sensitivity to new physics. NEA (Negative Electron Affinity) GaAs photo-cathode has been developed as a highly spin polarized electron source since 1970's [1]. The spin polarization is defined as the ratio of the difference of number of right handed and left handed electrons to the total number of electrons. Although it is limited fundamentally up to 50% with a bulk GaAs crystal, the strain super-lattice crystal of GaAs [2] realize 92% polarization by breaking the degeneration of the valence band. The strain compensated super-lattice GaAs [3] improves the crystal quality leading the quantum efficiency 1.6% with 90 % polarization.

In contrast to the many improvements of polarization and quantum efficiency, the robustness of the cathode has been very limited. The polarized electron emission requires NEA surface where the conduction band minimum state has higher energy than the vacuum state, because the electron excited to the conduction band have almost no momentum. The NEA surface is made by adsorption of Cs-O/NF$_3$ on a cleaned GaAs surface and the procedure making NEA surface is called as activation. In NEA surface, Cs and oxygen or NF$_3$ are weakly bound on GaAs surface and the electron

_____
* mkuriki@hiroshima-u.ac.jp

emission is easily lost by residual gas pollution [4], thermal desorption [5], Ion back bombardment [6].

An exact mechanism of NEA activation with Cs-O/NF$_3$ is not understood, but an hypothesis is electric dipole of the surface layer decreasing the energy state of vacuum. A possible NEA activation with CsTe was suggested by Sugiyama [7]. The author proposed NEA activation of GaAs with a thin layer of semi-conductor. It is called as NEA activation with hetero-junction of a thin semiconductor. The first NEA activation based on the hetero-junction hypothesis was confirmed with CsTe thin layer reported in Ref. [8, 9] and the lifetime improvement has been demonstrated in Ref. [10]. Figure 1 explains the NEA activation with the hetero-junction hypothesis. The horizontal axis shows normal direction of the cathode (z) and the vertical axis is the energy of states. From the left, the regions are GaAs, surface thin layer, and vacuum. The horizontal dashed line shows Fermi level. GaAs has a band gap with E_{BG} and Fermi level is at the bottom of the band gap in p-doped case. If the work function of the semiconductor is less than E_{BG}, the vacuum level is less energy than the conduction band minimum of GaAs, i.e. the surface state becomes NEA. The size of NEA is χ in the figure.
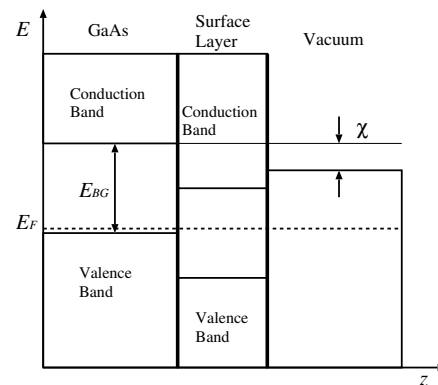

Figure 1: NEA surface state by the hetero-junction hypothesis. The horizontal and vertical axes show the normal direction of the cathode surface and energy state, respectively. From the left, the regions are GaAs, surface thin layer, and vacuum. The horizontal dashed line shows Fermi level. If the work function of the surface thin layer is less than E_{BG}, the surface state becomes NEA.

In the following sections, we present the experimental study of NEA activation of GaAs with CsKTe thin layer. CsKTe [11] is known as a thin film photo-cathode made by evaporation as same as Cs$_2$Te. The study is important to confirm the hypothesis of NEA activation with the hetero-junction.

NEA ACTIVATION

The experiment was carried out at Hiroshima University. Two inches bulk Zn-doped (5×10^{19}cm^{-3}) p-type GaAs (100) wafer was used. A quarter of the wafer was placed on a cathode mount in a vacuum chamber. Prior to the installation, the wafer was treated with a solution of H_2SO_4, H_2O_2, and H_2O, and another solution of HCl and C_3H_8OH (iso-propanol)to remove the oxidized surface layer and make an As rich surface [12]. These processes are done in air and the treated sample was stored in a desiccator at 0.1 Pa.

After the sample is installed in the vacuum chamber, the chamber is baked to established an ultra-high vacuum condition. A typical base pressure was 3.6×10^{-8}Pa. The vacuum chamber was pumped by ion pump and NEG pump. Before the experiment, the sample was heated up to 450 °C to obtain the cleaned surface.

Te beads is mounted on tungsten basket. By applying the current to the tungsten basket, Te vapor is generated. K and Cs vapor were generated with dispensers by SAES Co. These vapor sources were mounted on a movable head and the position can be adjusted to the sample position. The vapor source was designed to generate vapor symmetrically to the GaAs sample and a quartz thickness monitor to measure the amount of the evaporated metal. The amount of the metal on GaAs is controlled with the thickness monitor.

QE (quantum efficiency) is defined as the ratio of number of photo-electrons to number of photons. To measure QE of the cathode, monochromatic light from Xe lump with a grating monochromator is introduced to the chamber through a silica viewing port. The cathode mount is biased with -100 to measure the photo-current. The space charge effect is negligible with this condition.

After the sample was cooled down to RT (room temperature), the NEA activation was done with the following process.

1. Evaporate Te with a determined thickness.

2. Observe QE in the range from 250 nm to 1000 nm with 10 or 50 nm step.

3. Evaporate K with some thickness.

4. Evaporate Cs with the same thickness.

5. Repeat QE measurement and K and Cs evaporation.

6. If QE with 250 nm photon is saturated, we stop the process.

The condition established with these processes is called as the optimum condition. In this condition, QE with 250 nm photon is maximized. CsKTe cathode should have a high quantum efficiency in the UV region [11] and we expect that a good CsKTe thin layer is formed with this condition. Figure 2 shows the alkali metal thickness (sum of Cs and K thicknesses) of the optimum condition as a function of Te thickness. The line is a linear fit curve to the data points except one of 0 Te thickness. The thickness of the alkali

metal is proportional to Te thickness, i.e. the ratio of the alkali-metal and Te is constant for different Te thickness. This is an evidence of that a compound of Cs, K, and Te is formed on GaAs sample. Please note that the point of 0 Te thickness is off the line, because this is a compound of Cs and K (no Te) and should be a different compound.
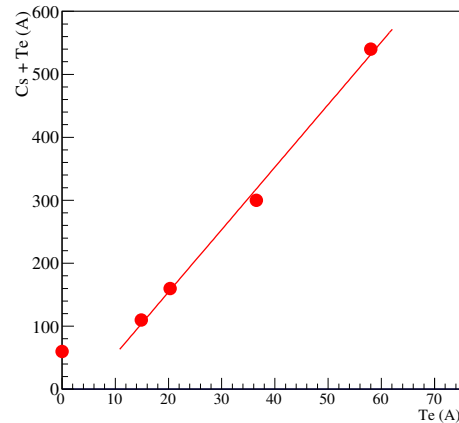

Figure 2: Total thickness of alkali metal (Cs + K) at the optimum condition as a function of Te thickness is plotted. Except zero thickness of Te, Total thickness of alkali metal is proportional to Te thickness.

Figure 3 shows the evolution of QE spectrum during the activation experiment. As mentioned already, Cs and K were evaporated repeatedly after Te was evaporated on GaAs surface with same amount. The number in legend is the sum of Cs and K thickness. In this case, Te thickness was 14 Å. 10 Å Cs and K were evaporated every time. 0 thickness Cs and K data (closed circle) shows zero quantum efficiency for less than 2.5 eV. By increasing the Cs and K thickness, QE in 1.4 - 2.5 eV region is increased and saturated for 80 Å or more Cs and K thickness. The spectra with Cs and K thickness more than 30 Å have a significant value at 1.43 eV which corresponds to GaAs band gap energy. QE at 1.43 eV with 100Å Cs and K was 1.5×10^{-5}. Background level is estimated as less than 1.0×10^{-6} in QE.

Electron emission with 1.43 eV photon is not from CsKTe states [11]. Surface intermediate states is a possibility to explain this emission, but the steep drop of QE at less than 1.43 eV is not consistent. The emission with 1.43 eV photon is consistent to the hetero-junction structure of GaAs and CsKTe thin film. 1.43 eV photon can penetrate the CsKTe thin film because the energy is less than the band gap of CsKTe. The photon excites the valence band electron of GaAs to the conduction band. Because the electron in the conduction band has almost no momentum, it moves to CsKTe by diffusion. Electrons in CsKTe obtains some momentum due to the energy difference between GaAs and CsKTe. Electrons in CsKTe are thermalized and some electrons whose momentum is less than the vacuum potential, are captured in CsKTe conduction band. A fraction of electrons can escapes to vacuum. This description is consistent

Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan
July 31 - August 3, 2019, Kyoto, Japan
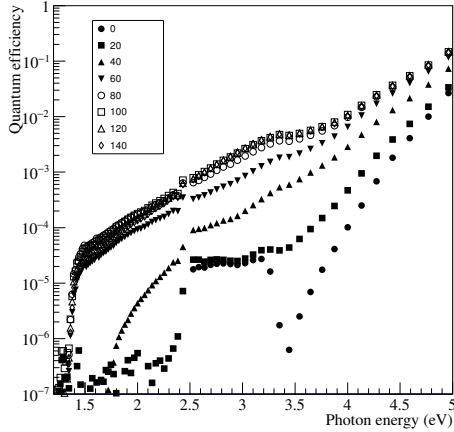
PASJ2019 FROH04

Figure 3: QE spectrum of GaAs activated with CsKTe (14 Å Te). Number of legend is the sum of Cs and K thickness.
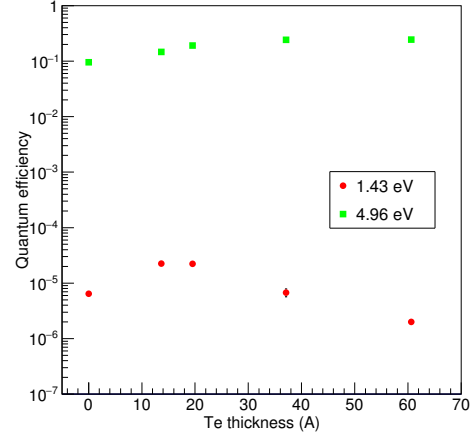

Figure 4: QE with 4.96 eV photon (green filled square) and 1.43 eV (red filled circle) are shown as a function of Te thickness. For each Te thickness, alkali metal (Cs and K) are applied to maximize QE with 4.96 eV photon.

to the steep drop of QE at less than 1.43 eV and the small QE at 1.43 eV. Considering these phenomena, the emission with 1.43 eV photon from the CsKTe-GaAs cathode strongly suggests the NEA activation of GaAs with CsKTe thin film.

Figure 4 shows QE as a function of Te thickness. For each Te thickness condition, alkali metal (Cs and K) are applied to maximize QE with 4.96 eV photon. The red filled circle shows QE with 1.43 eV photon, and the green filled square shows QE with 4.96 eV. According to the discussion in the previous paragraph, the emission with 1.4 eV photon is from GaAs and it with 4.96 eV photon is from CsKTe. 4.96 eV data shows QE increasing monotonically with thicker CsKTe layer and a saturation for more than 40 ÅTe thickness. This property is consistent to that the emission with 4.96 eV photon is from CsKTe layer. QE with 1.43 eV photon ie peaked around 10-20 Åand decreased for larger Te thickness. It is consistent that the emission with 1.43 eV is from GaAs. The decay of QE with thicker Te is light or electron absorption by the CsKTe layer.

Lifetime Measurement

Lifetime of the CsKTe-GaAs cathode was measured. After the activation, QE evolution in time was observed. This time, we measured the lifetime without beam emission, i.e. the beam current is negligibly small. In this case, the cathode QE is decreased by residual gas poisoning. The effect should depend on the vacuum pressure and gas species. By assuming the gas species does not change during the measurement, QE evolution $\eta(t)$ can be expressed as

$$\eta(t) = \eta_0 e^{-\frac{\int P dt}{\tau}}, \tag{1}$$

where η_0 is a constant, P is vacuum pressure, and τ is the lifetime. The dimension of τ is Pa.sec.

Figure 5 shows QE evolution for 2.06 eV photon. Te thickness was 37Å for this data set. Because the preceding researches evaluated the lifetime with this photon energy, we used the same photon energy for comparison. The horizontal
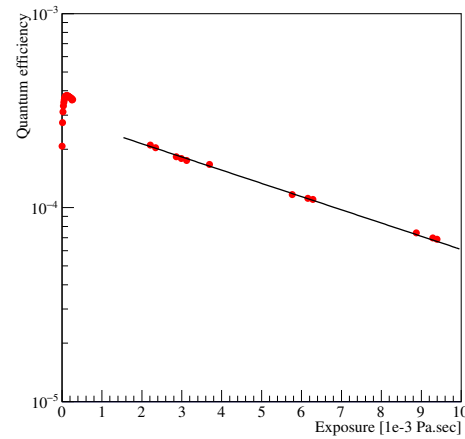

Figure 5: QE with 2.06 eV photon as a function of exposure (10^{-3}Pa.sec) is plotted. By fitting with the data > 2.0 × 10^{-3}Pa.sec, 1/e lifetime in exposure is obtained as 6.49 ± 0.01 × 10^{-3}Pa.sec.

axis show the exposure in 10^{-3}Pa.sec. The line is a fitting curve according to Eq. (1). $t = 0$ is the end of evaporation. The data points < $2.0 \times 10^{-3}Pa.sec$ are not included to evaluate the fitting curve. 1/e lifetime is evaluated as 6.49 ± 0.01 × 10^{-3}Pa.sec. This number should be compared to the preceding studies [13, 14] which are summarized in Table 1. The lifetime of CsKTe-GaAs cathode is 16 - 22 times longer

Table 1: Lifetime of NEA GaAs Cathodes

Cathode	Lifetime[10^{-3}Pa.sec]
CsKTe-GaAs	6.49 ± 0.01
CsO-GaAs	0.29 ± 0.03 [13]
CsO-GaAs	0.40 ± 0.02 [14]

Proceedings of the 16th Annual Meeting of Particle Accelerator Society of Japan
July 31 - August 3, 2019, Kyoto, Japan

PASJ2019 FROH04

than that of CsO-GaAs cathode.

The lifetime with 1.43 eV photon of CsKTe-GaAs cathode was $2.75 \pm 0.05 \times 10^{-3}$ Pa.sec. 1.43 eV photon is used for spin-polarized electron generation. According to this number, operational lifetime under various condition can be estimated. If we assume pressure in an RF gun and DC gun as 1.0×10^{-7} Pa and 5.0×10^{-10} Pa, the expected operational lifetimes are 7.8 hours and 1540 hours for RF and DC guns, respectively. The results are summarized in Table 2.

Table 2: Expected Operational Lifetime of CsKTe-GaAs Cathodes

Gun	Pressure [Pa]	Operational lifetime [h]
RF gun	1.0×10^{-7}	7.7
DC gun	5.0×10^{-10}	1540

CONCLUSION

We perform the experimental study of NEA activation with CsKTe thin film. Electron emission with 1.43 eV photon was observed and the result strongly suggested the NEA activation with CsKTe. The lifetime was measured with this cathode and the lifetime was $6.49 \pm 0.01 \times 10^{-3}$ Pa.sec with 2.06 eV photon which was 16 - 22 times longer than that with CsO-GaAs cathode. The expected operational lifetime of 1.43 eV photon with RF gun is 7.7 hours. The result demonstrated the effectiveness of NEA activation with the hetero-junction hypothesis and improving the robustness of the NEA GaAs cathode. It suggests a possibility of polarized RF electron gun with this cathode.

ACKNOWLEDGEMENTS

REFERENCES

[1] D.T. Pierce *et al*., Appl. Phys. Lett. 26(1975)670.

[2] T. Nishitani *et al*., J. Appl. Phys. 97(2005)094907.

[3] X. Jin *et al*.,Appl. Phys. Lett.,105(2014)203509.

[4] N. Chanlek *et al*., J. Phys. D: Appl. Phys.,5(2014)055110.

[5] M. Kuriki *et al*., Nucl. Inst. and Meth. A, 637(2011)S87-S90.

[6] J. Grames *et al*., *Proc. of PAC 2005*(2005)WPAP045.

[7] H. Sugiyama *et al*.,J. Phys. Conf. Ser. 298(2011)012014.

[8] M. Kuriki *et al*., *Proc. of IPAC 2015*(2015) TUPWA062.

[9] K. Uchida, Master Thesis of Hiroshima University(2014).

[10] J. Bae *et al*., *Proc. of IPAC2015* (2015) TUPML025.

[11] D. Bisero *et al*., Appl. Phys. Lett. 70(1997)1491.

[12] Q.E. Tereschenko *et al*., Appl. Surf. Sci. 142(1992)75-80.

[13] K. Miyoshi, Master Thesis of Hiroshima University (2013).

[14] L. Guo, Master Thesis of Hiroshima University (2012).