NEA SURFACE ACTIVATION OF GaAs PHOTOCATHODE WITH CO_2

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Abstract

NEA (negative electron affinity)-GaAs cathode is able to generate highly spin polarized electron beam more than 90%. The NEA activation is performed usually with Cs and O_2 or NF_3, but the exact structure of the NEA surface is not known. In this paper, we performed the NEA activation on a cleaned GaAs surface with CO_2, CO and O_2 gases and compared the results to improve our understanding on the NEA surface. We found that CO_2 activated the cathode, but CO did not. By analyzing CO_2 activation, we found that atomic oxygen activates the NEA surface and CO degrades the NEA surface simultaneously. We found that the NEA activation ability of atomic oxygen is almost a half of that of O_2 molecule.

INTRODUCTION

NEA (Negative Electron Affinity) GaAs photo-cathode has a unique and important role in the accelerator science. This is a practically only solution of highly spin polarized electron source for accelerator [1] [2]. NEA GaAs cathode is also useful as a high brightness (large current and small emittance) electron beam, due to the small beam emittance [3] and a large quantum efficiency (QE) up to 20% [4]. It can be considered to be one of the candidates of photo-cathode for accelerators requiring a high brightness electron beam.

In contrast to the large improvement on the spin polarization and the good performance of the beam from the NEA cathode, the structure of the NEA surface is not understood well. The NEA surface is artificially formed by Cs evaporation with O_2 [5] of NF_3 [6] evaporation on a cleaned GaAs surface. According to an investigation of the NEA surface by STM, the work function of p-GaAs(110) was lowered by Cs adsorption on its surface [7], but the role of O_2 or NF_3 in the NEA activation has not been understood well. By analyzing spectra of QE of NEA GaAs, it is suggested that the thickness of the surface potential is decreased by progress of Yo-Yo process [8].

To improve our understanding for the NEA surface, we studied the NEA activation process with several gas species. In this paper, we employed CO_2 and CO as test gases. We performed the NEA activation experiment with them. The results were compared with that by O_2 as reference.

EXPERIMENT

The experimental setup and the gas introduction system were described in Ref. [9]. The typical pressure was 6.0×10^{-9} Pa. The GaAs wafer is placed on a molybdenum base plate. It is soldered on the base with indium and fixed by a tantalum cup. In this study, the p-type, Zn-doped bulk GaAs(100) was used as a cathode sample. The doping density is $4.0\times10^{19}\text{cm}^{-3}$. The temperature of the cathode mount can be controlled with a tungsten heater embedded in the mount. The GaAs cathode temperature is measured with a thermocouple attached to the cathode mount. A quadrupole mass spectrometer, QMS (M101QA-TDM-W, ANELVA) is used for the gas analysis. The sample gas contains not only the specific molecule, but also fragment components and contaminations. The gas content is obtained by analyzing the mass-to-charge ratio (m/z) spectrum up to 100 m/z measured by QMS.

The NEA GaAs cathode was formed by alternate evaporations of Cs and gas (O_2 as reference) on a cleaned GaAs substrate (yo-yo method) [9]. We examined CO_2 and CO as the test gas. Addition to these gas species, O_2 was used as the reference. The QE evolutions during the NEA activation with O_2, CO_2 and CO are shown in Figures 1-3, respectively.

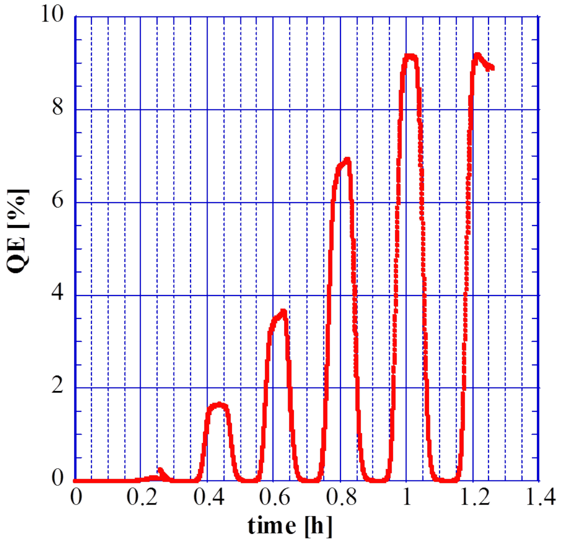

Figure 1: QE evolution during the activation process by Cs and O_2. The first peak is made by Cs only. In other peaks, QE is increased by O_2 and decreased by Cs.

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Figure 1 shows the QE evolution of the NEA activation with O_2 gas. The first peak is made by Cs evaporation. In other peaks, QE is increased by O_2 and decreased by Cs. If the height of the peak is almost same as that of the previous peak, as the sixth peak in Figure 1, we terminate the NEA activation process. Figure 2 shows the QE evolution of an activation with CO_2. The first peak is made by Cs evaporation. In other peaks, QE is increased by CO_2 and decreased by Cs. The evolution is similar to that with O_2, but the maximum QE value is about 2.3% which is significantly lower than that with O_2.

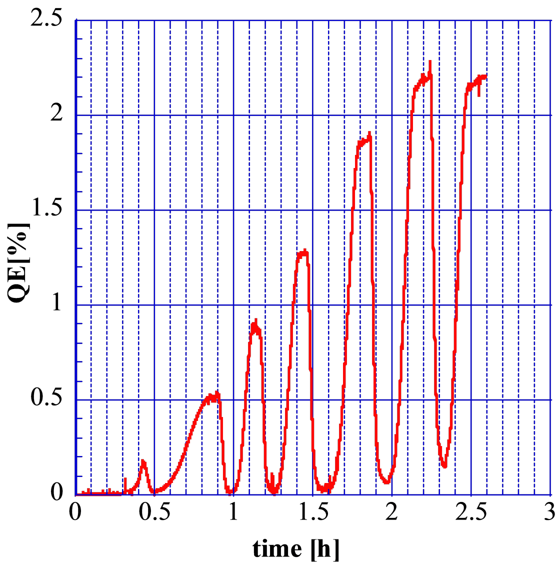

Figure 2: QE evolution of the activation process with Cs and CO_2. The activation procedure was same as that with O_2 except the introduced gas.

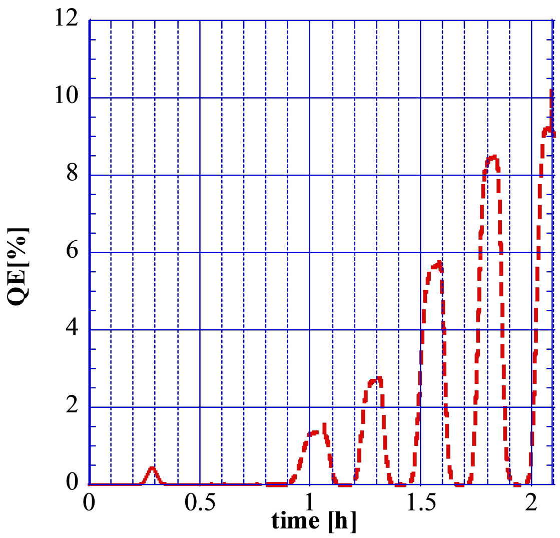

Figure 3: QE evolution during the activation process with Cs and CO. QE did not rise with CO.

Figure 3 shows the QE evolution of an activation with CO. After the first peak was made by Cs, CO gas was introduced up to t=0.8 h, but nothing happened, i.e. QE was not increased at all. CO did not activate GaAs cathode. To confirm the health of the GaAs sample and effect of CO on GaAs, O_2 gas was introduced after t=0.9 h, i.e. the usual NEA activation was performed. In Figure 3, QE evolutions of the NEA activation with CO and O_2 are drawn with a solid line and a dashed line, respectively. By introducing O_2 gas, QE was increased as same as the usual NEA activation with O_2 and the final maximum QE was more than 9% which is almost same as that in Figure 1. From this result, we can conclude that the GaAs sample was healthy (there was no trouble on the preparation) and CO does not activate GaAs cathode. CO gas introduction prior to the process does not disturb NEA activation with O_2, because the NEA surface was activated with O_2 even after CO gas was applied.

DISCUSSION

Figure 4 shows the height of each peak in the Figure 1 (NEA activation with O_2) as a function of exposure of O_2 gas in Langmuir ($1\text{L} = 1.33 \times 10^{-4}\text{Pa} \cdot \text{s}$). According to the result, the height is linearly increased as the O_2 gas exposure. Figure 5 shows the height of each peak in the Figure 2 (NEA activation with CO_2) as a function of exposure of CO_2 gas. It is quite different from Figure 4. The QE height in Figure 4 is proportional to the exposure of O_2, but the relation of that with CO_2 in Figure 5 is not linear.

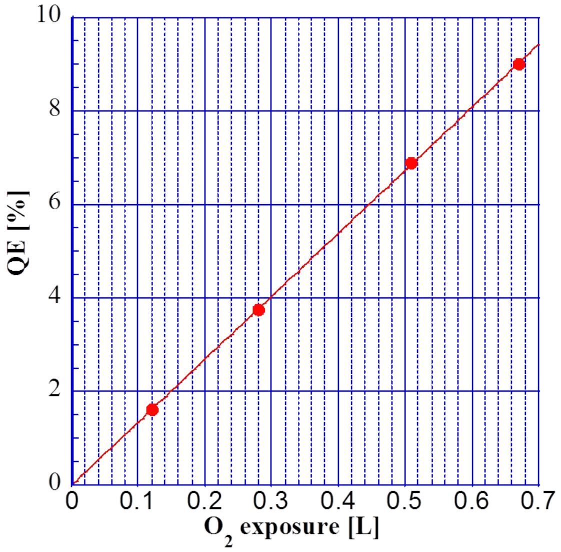

Figure 4: The height of each peak in Fig. 1 is shown as a function of O_2 gas exposure. The red solid line is a fitting curve by assuming Eq. (2).

CO molecule does not contribute to the NEA activation and does not disturb the NEA activation process, but it degrades the activated NEA surface, according to Ref. [10]. By considering this degradation effect of CO molecule, the saturation observed in Figure 5 can be explained. The QE(η)

evolution of the CO_2 activation can be expressed by the degradation effect by CO molecule and the activation by atomic oxygen as

$$\eta = \frac{\alpha_1 \mu}{\beta}[1 - \exp(-\beta x_3)] \tag{1}$$

where $\mu f_3 = f_1$. $x_3 = \int_0^t f_3 dt$, i.e. exposure of CO. This model can explain not only the lower QE of the activation with CO_2 than that with O_2, but also the non-linearity of the curve in Figure 5.

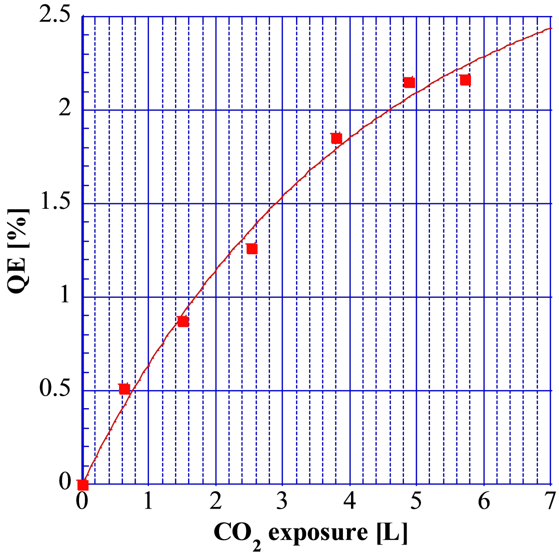

Figure 5: The height of each peak in Fig. 2 is shown as a function of CO_2 gas exposure. The red solid line is a fitting curve by assuming Eq. (1).

The content of CO_2, CO, and atomic oxygen in the experimental chamber were measured with QMS. The measured mass spectrum (m/z) is a convolution of the gas content, sensitivity coefficient and fragmentation pattern coefficient of each component [11] [12]. We assume O, C, CO, N, N_2 and CO_2 as the content. By analyzing the data with the pattern coefficient of QMS [11], the partial pressure of these molecules during the experiment can be extracted. For example, the peak at 44 is composed by CO_2 only. Because a part of CO_2 fragments into CO(m/z=28), O(m/z=16), and C(m/z=12) , these components has to be accounted. The fraction of CO_2, CO, and O during the experiment was estimated to be 0.75:0.18:0.07. μ is 0.39.

As same as that for CO_2 case, the content was estimated with the same manner, when O_2 gas was introduced. O_2 molecule composes peaks at 32 (O_2) and 16 (O) as the fragment product, but atomic oxygen composes only a peak at 16. The fraction of O_2 molecule and atomic oxygen during the experiment was estimated to be 0.75:0.25. To determine both activation ability of the O_2 molecule and atomic oxygen independently, the NEA activations with CO_2 and O_2 gas were analyzed together. The expected evolution of the quantum efficiency η for the activation with O_2 is

$$\eta = \alpha_1 x_1 + \alpha_2 x_2, \tag{2}$$

where α_2 is the activation ability of O_2 molecule and x_2 is the exposure of O_2 molecule.

Three parameters, α_1, α_2, and β can be determined with the data of activations with O_2 and CO_2. The results are shown in Figure 4 and 5 as the fitting curves. α_1 and α_2 (activation abilities of atomic oxygen and O_2 molecule) were estimated to be $7.7 \pm 0.1\ L^{-1}$ and $15.4 \pm 0.1\ L^{-1}$, respectively. The error of α_1 and α_2 are estimated by three measurements with CO_2. The center value is the average and the error was half of the peak-to-peak value. We found that O_2 molecule has an activation ability that is approximately twice of that of atomic oxygen. This fact can be explained as that the activation ability is simply proportional to the number of atomic oxygen provided to GaAs-Cs surface. The degradation ability β of CO was estimated to be $0.91 \pm 0.09\ L^{-1}$ which can be compared to $0.84\ L^{-1}$ in Ref. [10]. These numbers are consistent to each other within the error. The error of β is estimated with the same manner for α.

SUMMARY

We examined the NEA activation of GaAs cathode with O_2, CO_2 and CO to understand NEA surface property. In a nominal activation with O_2 gas, we found that the height of each yo-yo peak are proportional to O_2 exposure. CO did not activate the NEA GaAs cathode at all. CO_2 activated the NEA GaAs cathode, but the QE was 2.3% which was lower than that with O_2. We found that the activation ability of O_2 molecule and atomic oxygen were $15.4 \pm 0.1\ L^{-1}$ and $7.7 \pm 0.1\ L^{-1}$, respectively. The low quantum efficiency of the cathode activated with CO_2 can be explained with the degradation by CO to the NEA surface. The degradation ability of CO was estimated to be $0.91 \pm 0.09\ L^{-1}$, which is consistent to 0.84 by a preceding study [10].

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