# SUBSTRATE DEPENDENCE OF CSK2SB CATHODE PERFORMANCE

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*Abstract*

$CsK_2Sb$ is a high performance cathode which can be driven with a green laser. The cathode is generated by evaporation on a substrate in a high vacuum environment. The cathode was evaporated on various material and surface condition to evaluate the dependence of the cathode performance. GaAs (100), Si(100), and Si(111) were examined as samples of the substrate. For each materials, the cathode on the cleaned and as-received substrates were examined and those on the cleaned showed better performance than the as-received for all materials. The detail of the experimental results are presented.

## INTRODUCTION

In linear-accelerator-based advanced accelerators, the performance of the accelerated beam strongly depends on the initial beam property. Therefore, the beam performance from the source is important. Multi-alkalis are a group of materials composed from two or more alkali metals. Multi-alkali materials have been used as photo-cathodes in photo-multiplier tubes. The multi-alkali cathode is considered to be the strongest candidate as a high brightness electron source because it can be operated by green light (532 nm) with 10% QE [1] [2], which is easily obtained from the second harmonics of a solid-state laser. Moreover, the multi-alkali cathode has a long operational lifetime [3].

$CsK_2Sb$ cathode is fabricated as a thin film on a substrate by evaporation in an ultra-high vacuum environment. Various materials have been examined as the substrate, e.g. Glass(amorphous) Cu(amorphous) [4] Mo(amorphous), Mo(100), Si(100) [2], GaAs(100) [5], where the numbers in parenthesis are the surface direction of the crystalline substrate. Cathodes fabricated on the amorphous substrates (Glass, Cu, SUS, and Mo) showed relatively low QE as 1-5% with 532nm laser light [6] [7] [8] [4] [9]. In contrast, cathodes fabricated on crystalline substrates (Si(100), Mo(100) and GaAs(100)) showed relatively high QE as 7-10% with 532nm laser light [10] [2] [5]. These results suggest that the substrate crystallinity has an impact on the cathode performance.

To study the cathode performance dependence on the substrate material, surface condition, crystallinity, $CsK_2Sb$ cathode was fabricated on Si(100), Si(111), and GaAs(100) and the performance was compared.

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## EXPERIMENT

The experimental setup was described in Ref. [1] in detail. The cathode was fabricated in a vacuum chamber at a typical pressure of $1.0\times10^{-8}$ Pa. The cathode substrate is fixed on a molybdenum puck. The puck is mounted on the cathode holder during evaporation and electron emission. In this study, Si(100) and Si(111) p-type wafers with a resistivity of $\leq 0.002\ \Omega\mathrm{cm}^{-1}$ and GaAs(100) p-type wafers are employed as the substrates.

Si wafer was etched, single side polished and finally washed with RCA method by the Sales Company. GaAs wafer was etched, double-side polished, and finally washed with RCA method, as well. The Si(100) and Si(111) substrates were processed with a 5% HF solution for about 5 min to remove the surface oxidized layer. The GaAs surface was processed with a $H_2SO_4$:$H_2O_2$:$H_2O$ (4:1:1) solution for about 5 min to remove the surface oxidized layer [11].

The surfaces of Si(100) and Si(111) are equivalent except the surface direction after the HF treatment. This cleaned surface is kept for 3 and 50 hours in air for Si(100) and Si(111), respectively [12]. In our experiment, after the cleaning, the Si sample was kept in a desiccator (typical pressure was 1Pa) and the air exposure duration during the sample transfer was totally less than 30 minutes and the re-oxidation on the substrates are negligible. Therefore, the Si(100) and Si(111) substrates in out experiment are equivalent except the surface atomic arrangement.

To examine the effect of the surface oxidation, we also examined the as-received substrates. The atomic arrangement of the as-received surface is disturbed by the oxidation layer, and it is considered to be amorphous.

The evaporation sources are mounted on a linear movement mechanism in the chamber. The high-purity (99.9999%) Sb pellets were resistively heated in a tungsten evaporation basket. The K and Cs sources are dispensers provided by SAES Co., Ltd.. The amount of material on the substrate was monitored with a quartz thickness monitor (INFICON Q-pod Quartz Crystal Monitor).

To control the cathode temperature, a tungsten heater is used. The heater is mounted on the head of the linear mover, which can be inserted from back side of the cathode puck. The cathode puck temperature is measured with a thermocouple.

Typically the $CsK_2Sb$ cathode was formed by sequential evaporation of Sb, K, and Cs on a substrate. 10 nm Sb was evaporated at 100°C substrate temperature giving maximum QE with less fluctuation [1]. Amount of K and Cs are automatically determined to maximize QE after each evaporation,




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Table 1: The maximum QE of the $CsK_2Sb$ photo-cathode on Mo(100), Mo(amorphous), Si(100), Si (111), and GaAs (100) substrates at 532 nm are summarized.

| Substrate | Surface treatment | QE[%]@532nm |
|---|---|---|
| Mo(100) | Polished+sputter | 10.0 [10] |
| Mo(amorphous) | Polished+sputter | 2-5 [8] [9] |
| Si(100) | as-received | $4.8 \pm 0.6$ |
| Si(100) | 5%HF | $9.4 \pm 0.7$ |
| Si(100) | 5%HF | 7 – 10 [2] |
| Si(111) | as-received | $1.6 \pm 0.1$ |
| Si(111) | 5%HF | $2.3 \pm 0.3$ |
| GaAs(100) | as-received | $5.5 \pm 0.2$ |
| GaAs(100) | $H_2SO_4$:$H_2O_2$:$H_2O$ | $10.0 \pm 0.2$ |

i.e. we stopped the evaporation whenever QE is saturated. The evaporation procedure is explained in Ref. [1].

The cathode was biased at -100 V, and the photo-current was measured as the current of the bias supplier. The results (maximum QE) are summarized in Table 1 including the results of the preceding studies. We repeated the evaporation five times for each substrate. The error is obtained as the standard deviation of the five measurements. The QE of the as-received substrate was around 2.5-5.5% at 532 nm. The cleaned Si (100) and GaAs(100) substrates showed a good QE as high as 10%. These results are similar to those of the cleaned Mo(100) [10] and Si(100) substrates [2]. In contrast, the QE of the cleaned Si(111) was higher than that of the as-received Si(111), but it is much lower than that of the cleaned Si(100) and GaAs(100) substrates.

According to results shown in Table 1, the cathode performance developed on the cleaned substrate was significantly higher than that on the as-received substrate for all cases. We could not conclude that the substrate crystallinity has an impact on the cathode performance, because the chemical property of the oxidized surface may differ from the clean one, but it can be a collateral evidence. The cathode formed on the Si(111) substrate showed the least performance in the tested substrates in both the cleaned and as-received cases. The difference in the cathode performance on the Si(100) and Si(111) substrates provide direct evidence that the cathode performance depends strongly on the substrate direction, because the material properties of Si(100) and Si(111) are exactly same otherwise. A similar conclusion was also obtained by comparing QE of the crystalline Mo(100) [10] and amorphous Mo [8] [9], because the physical property of the crystalline and amorphous Mo other than the surface atomic arrangements, are almost same. Mo(100) and Mo(amorphous) substrates in Reference [10] [8] [9] are considered to be cleaned because it was polished and sputtered.

## DISCUSSION

Crystalline $CsK_2Sb$ forms a $DO_3$ cubic structure [14] [15]. The unit cell contains four formula units and is represented

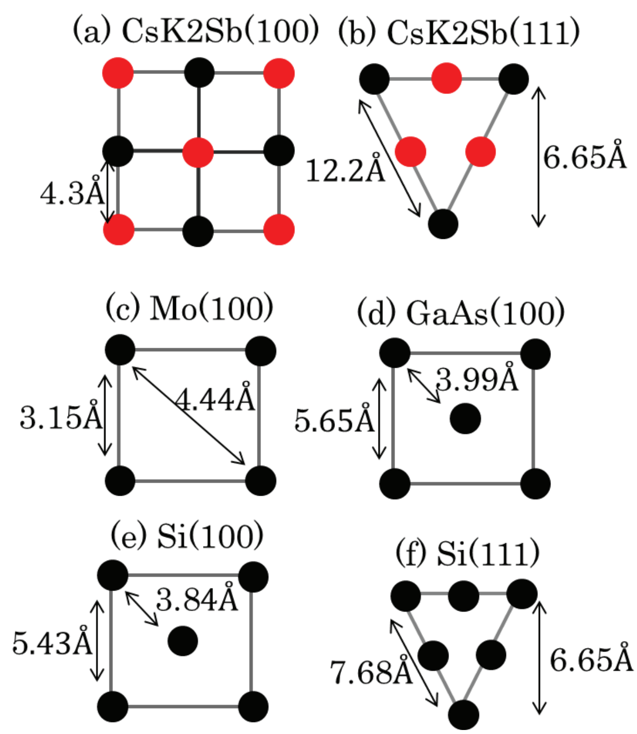


Figure 1: Atomic arrangement of $CsK_2Sb$(100) and $CsK_2Sb$(111) on the Mo(100), GaAs(100), Si(100), and Si(111) surfaces. The lattice constants of Mo, Si, and GaAs are 3.15Å, 5.43Å, and 5.65Å, respectively [13].

by four face-centered sub-lattices shifted by $a\sqrt{3}/4$ ($a$ is a lattice constant of the primitive translation vector) along the body diagonal [14] [16]. The lattice constant $a$ is 8.61 [14] [15] [17].

Figure 1 shows that the surface atomic arrangements of $CsK_2Sb$(100), $CsK_2Sb$(111), Mo(100), GaAs(100), Si(100), and Si(111) surfaces. By considering the matching between the atomic arrangements among $CsK_2Sb$ (100), (111), Si(100), Mo(100), and GaAs(100) surfaces, $CsK_2Sb$ are grown in (100) direction on Si(100), Mo(100), and GaAs(100) surfaces, and in (111) direction on Si(111) direction.

The reason for the reduced performance of the as-received substrates comparing to the cleaned substrates could be the less quality of $CsK_2Sb$ crystal. Oxidation distorts the atomic arrangement of the substrate surface resulting a poor matching between the substrate and $CsK_2Sb$ crystals. The poor matching leads to a lower quality of $CsK_2Sb$ crystal grown on the substrate and reduced performance.

The cathode on the cleaned Si (100) and GaAs(100) substrates showed a good QE as high as 10%. These results are similar to those on the cleaned Mo(100) and Si(100) substrates obtained by the Cornell group [10]. On the other hand, the cathode performance on Si (111) is less than the others. These results can be explained with the band structure of $CsK_2Sb$. In References [14] [15], the bulk band dispersion of $CsK_2Sb$ was calculated. The point on the boundary surface of the Brillouin region is called the K, L, and X points in the (110), (111), and (100) directions, respectively. According to the bulk band dispersion, $CsK_2Sb$ is a direct transition type at the Γ point with 1.1 eV bandgap. The bandgap is about 2.1, 3.1, and 1.4eV at K, L, and X, respectively. If we consider the photo-electron emission in (100) direction, not only electrons at Γ point, but also electrons at X point contributes to the emission, because the bandgap at X point is similar to that at Γ. On the other hand, for the photo-electron emission in (111) direction, there is no contribution at L point, because the bandgap energy (3.1 eV) is larger than the laser photon energy (2.3 eV at 532 nm). The photo-electron emission of $CsK_2Sb$ in (111) direction is possible only at Γ point and this is the reason why the quantum efficiency of (111) surface is less than that of (100) surface.

By a similar consideration, the QE of (110) surface should be less than that of (100) surface. In the preceding studies [18] [19], $CsK_2Sb$ was grown in (200) or (220) directions on Si (100) substrate, depending on the case and the cathode performance of (200) and (220) were similar [18]. We consider that the cathode evaporation conditions in these experiments were not fully optimized, because the QE is only 3% for 532 nm light in both cases. That is why $CsK_2Sb$ crystal direction depends on the case and there was no significant difference on the cathode performance grown in (100) and (110) directions in these studies.

In our case, the cathode evaporation condition was carefully optimized and the cathode performance reproducibility was quite good. The cathode performance dependence on the substrate crystallinity and the surface direction was confirmed based on the reliable experiments.

The application based on the linear accelerator (e.g. FEL, ERL, etc.) sometimes requires an extremely high brightness electron beam and the photo-cathode has to directly provide such beam. The high performance cathode is one of the most important devices in the advanced accelerator in this context. We found that the quantum efficiency depends not only on the substrate material and cleanness (chemical condition), but also crystallinity and the surface direction. This fact has an impact on the experimental physics with accelerators, because there is some potential to improve a thin-film cathode performance by revisiting the substrate crystallinity and surface direction of the substrate. The high quantum efficiency has a large merit to generate a high brightness electron beam by relaxing requirements for the drive laser. The fewer requirements for the laser make the system reliable, and stable. The availability of the system is improved and the effective cost of the project (cost per operation time) becomes less. Our result has a potential of the large impact on the accelerator science from this point of view.

## SUMMARY

We studied the substrate dependence of $CsK_2Sb$ photocathode performance. We found that the cleaned substrates resulted in higher performance than the as-received substrates for all materials. By comparing cathodes on GaAs(100), Si(100), Si(111), and Mo [10] [8] [9], we found that the cathode on GaAs(100), Si(100), and Mo(100) had significantly better performance than that on Si(111) and Mo(amorphous). It showed that the cathode performance depends strongly not only the substrate material and surface state, but also the crystallinity and the surface direction. We obtained the first experimental evidence about substrate surface direction dependence of $CsK_2Sb$ photo-cathodes performance.

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