

## DEVELOPMENT OF MULTI-ALKALI PHOTOCATHODE DEPOSITED ON $\text{LiTi}_2\text{O}_4$ SUBSTRATE FOR SRF-GUN \*

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### Abstract

We have manufactured the back-illuminated superconducting photocathode for the FEL with high pulse repetition. The novelty of this photocathode is adopting the transparent superconducting thin film  $\text{LiTi}_2\text{O}_4$  as a substrate. The reason for using LTO is to reflect RF by using feature of penetration depth of superconductor, which is defined from London equation. This feature protects optical components from RF damage. These are able to make a high quality beam which is a low energy spread and a low space spread. This paper presents a summary of the experiment, a brief overview of our activities and outlines future plans.

### INTRODUCTION

#### SRF-Gun

We have started a feasibility study of free electron laser (FEL) based on linear accelerator with high pulse repetition about 1MHz as a candidate for the next radiation light sources. We thought a combination of superconducting RF cavity and photocathode is an optimal electron gun for the new accelerator. In addition, we expected that irradiating an excitation laser from the back of the photocathode. An electron beam is accelerated in highly voltage circumstances in superconducting cavity, then the deflecting an electron beam in the accelerate phase is suppressed. The space distribution of the excitation laser is able to be controlled more precisely than case of irradiating from front of the cathode (the direction where an electron is emitted), then the pointing stability of an excitation laser is increased [1] and space charge effect is decreased. These are able to make a high quality beam which is a low energy spread and a low space spread.

To develop the back-illuminated photocathode, it is necessary to use a transparent substrate such as a sapphire glass and a diamond. However a sapphire glass substrate is difficult to operate with a superconducting RF cavity because it has a low withstand voltage (5kV/mm) to a high frequency thereby an electric discharge occurs. A diamond substrate is also difficult to operate stably because it has a low transmittance at the visible light region, so that the excitation laser of an ultraviolet region has to be controlled precisely. Furthermore, a light fiber and lens settled the back of the cathode are damaged because a high frequency through these substrates.

It is necessary to adopt the conductivity material to cut off the high frequency. But the transparent conducting material for example ITO cut off both a high frequency and an excitation light because the penetration length of the normal conducting material to high frequency is a few tens of micrometers. On the other hand, the superconducting material cut off a high frequency only a few hundreds of nanometers. Then we adopt the transparent superconducting thin film  $\text{LiTi}_2\text{O}_4$  as the substrate of our photocathode.

#### Transparent Superconductor $\text{LiTi}_2\text{O}_4$

Figure 1 shows the appearance of  $\text{LiTi}_2\text{O}_4$ . LTO was manufactured at Tohoku University in 2012 [2]. It is an epitaxial thin film deposited by using PLD (Pulsed laser deposition) on  $\text{MgAl}_2\text{O}_4$  (111) substrates. Table 1 shows the physical property of LTO. According table 1 data, LTO has a highly superconducting transition temperature ( $T_c$ ) and a transmittance. Its high density which does not depend on the temperature is the origin of the blue color. At superconducting states, the transmittance can be expected higher than at R.T. because the hall mobility becomes larger in lower temperature. Furthermore higher



Figure 1: The picture of  $\text{LiTi}_2\text{O}_4$ .

Table 1: Physical Property of  $\text{LiTi}_2\text{O}_4$

<b><math>T_c</math></b>	~ 12K
<b>Resistivity</b>	$3.3 \times 10^{-4} \Omega\text{cm}$ (at R. T.)
<b>Lattice constant</b>	$a_{LTO} = 0.8405 \text{ nm}$
<b>Transmittance</b>	70 % (at 477 nm)
<b>Carrier density</b>	$\sim 1 \times 10^{22} \text{ cm}^{-3}$
<b>Hall mobility</b>	0.8 (280K), 6.0 (15K) $\text{cm}^2\text{V}^{-1}\text{S}^{-1}$

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quantum efficiency can be expected by adopting LTO because the lattice constant of LTO is 0.8405 nm and close to that of multi-alkali  $K_2CsSb$  ( $= 0.861$  nm [3]).

However, LTO is a new material, so that its properties are not clear. Then we have measured the basic properties of this photocathode, such as magnetic susceptibility measurement, and photoelectron spectrometry, etc.

### Back-Illuminated Photocathode

Figure 2 shows a schematic block diagram of the photocathode that we are developing. This photocathode has a four layer structures, an excitation laser is illuminated through the AR coating surface. The thickness of MAO substrate is 0.5 mm and that of LTO is about 200 nm because the penetration depth of RF is about 170 nm. A multi-alkali layer,  $K_2CsSb$  is deposited on LTO. Because the temporal response of photocathode is higher than that of thermal cathode, we adopt a photocathode to realize high pulse repetition.  $K_2CsSb$  has high quantum efficiency ( $> 30\%$  at 405 nm) at ultraviolet region and a long life [4]. We plan to operate this photocathode under the superconducting transit temperature of LTO by using triple wave the YAG laser (355nm).

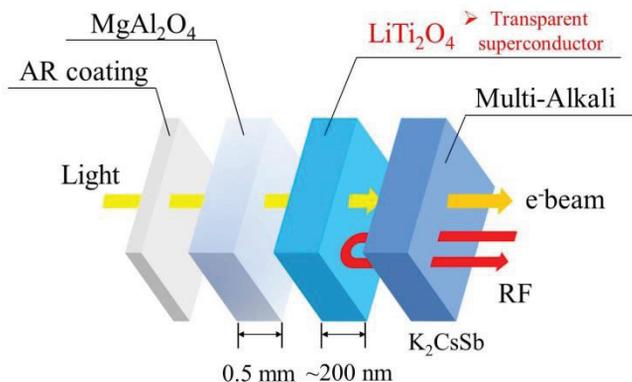


Figure 2: Back-illuminated superconducting photocathode.

In order to evaluate this photocathode, it is necessary to measure quantum efficiency, an initial emittance, a life time, critical magnetic field, withstand voltage and thermal conductivity under low temperature and high RF field condition. In this paper, we describe the apparatus to evaluate the photocathode which we have developed, and present some preliminary results from deposition measurements of  $K_2CsSb$ , the emittance measurement and the critical magnetic field measurement.

### EXPERIMENTAL SET UP

Figure 3 shows the schematic block diagram of the deposition apparatus and the initial emittance measuring apparatus.

#### Deposition Apparatus

This deposition chamber has cylinder shape with diameter: 150 mm and height: 520 mm. The cathode holder is fixed to the tip of the rod which is lengthened from the upper chamber. Four evaporation sources are installed and each material is deposited to a substrate which is put on in the center of the cathode holder. We calibrated the electric current through the evaporation source and the deposition thickness by the thickness meter at the cathode holder position. Each evaporation source can be adjusted at the insert position, and then the cylinder is closed with a shutter to prevent deposit of other deposition metal. Quantum efficiency is measured by injecting an excitation laser from the front, back and side of the chamber. The cathode plug can be transferred to other chambers by using transfer rods.

#### Emittance Measuring Apparatus

This apparatus consist of the emittance measuring chamber manufactured in reference to LBNL [5] and the stock chamber. The cathode holder is attached at the center of the former chamber and the cryostat is inserted from top of the chamber to the holder to cool a photocathode. The cathode can be cooled to about 4K by

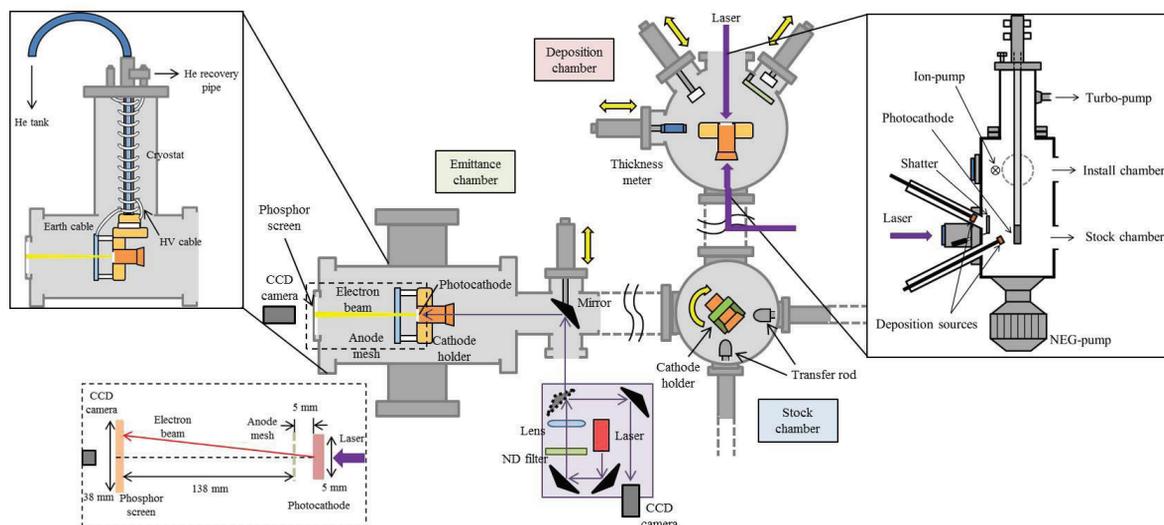


Figure 3: Schematic block diagram of measurement system.

supplying liquid helium through this cryostat. The anode mesh made of a nickel thin film is attached to the cathode holder. Electrons are accelerated in a high gradient cathode—anode gap  $g$  (5 mm) to a grid (pitch 50  $\mu\text{m}$ ), and then allowed to drift a distance  $d$  (138 mm) to a phosphor screen where they are imaged by a telecentric lens coupled CCD camera. In our measurements, the voltage applied to the cathode (V) was varied from -1 kV to -10 kV, giving a field gradient range of 0.2 to 2 MV/m. The excitation laser from an optical system placed in the chamber outside is reflected on the mirror and made incident to the back of a cathode. Light from a laser source was focused onto the cathode with a spot size of  $\mu\text{m}$ . The laser wavelength was 405 nm in this experiment.

## EXPERIMENTAL RESULTS

### Deposition Measurement of $\text{K}_2\text{CsSb}$

Table 2 shows the summary of deposition measurement of  $\text{K}_2\text{CsSb}$ . The vacuum during the deposition was  $6 \times 10^{-8} \sim 1 \times 10^{-7}$  Pa. In each case, an optically polished substrate was heated to 470 deg. for 3h before evaporating. Typically, a 10 nm layer of Sb was deposited at the substrate temperature of 150deg. Then, K was evaporated at a substrate temperature of 120 deg. until a maximum in the electron yield was observed. In the final step, Cs was deposited at a substrate temperature of <120 deg. until a maximum in the electron yield was observed. Three kinds of substrates (Mo, Cu, and  $\text{SrTiO}_3$ ) are measured. STO substrate is a semiconductor and has a transmittance of 70% over 400nm. The purpose of adopting a STO substrate is to confirm the electron emission by back-illumination and the occurrence of chemical reactions in the interface of an alkali metal and titanium oxide.

We achieved 7.5% of quantum efficiency with the Mo substrate, 13.7% with the Cu substrate and 8.0% with the

Table 2: Summary of Deposition Measurement at 405 nm

	Substrate	Sub. Temp. (deg)	QE (%)
$\text{K}_2\text{CsSb}$	Mo	$100 \pm 5$	6.2
	Mo	$100 \pm 5$	7.5
	$\text{SrTiO}_3$	95~110	6.96
	$\text{SrTiO}_3$	155~170	8.0
	$\text{SrTiO}_3$	$160 \pm 5$	0.68
	$\text{SrTiO}_3$	$160 \pm 5$	3.95
	$\text{SrTiO}_3$	$120 \pm 5$	4.2
	Cu	150~100	13.7
	Cu	150~100	6.7

STO substrate in excitation wavelength 405nm.

Furthermore, we confirmed the difference of quantum efficiency between the front-illumination and back-illumination by using the sample of STO substrate. In case of front-illumination, the quantum efficiency is 2.5%. On the other hand, in case of back-illumination, the quantum efficiency is 2.3%; Even if there is reflection and absorption of a substrate, the incident direction of excitation laser does not have a big influence to the quantum efficiency.

Figure 4 shows the wavelength dependence of quantum efficiency of  $\text{K}_2\text{CsSb}$  in each substrate. All substrates show a similar tendency and this tendency is consistent with those seen in the previous works [6]; therefore, we think that we could manufacture  $\text{K}_2\text{CsSb}$  properly.

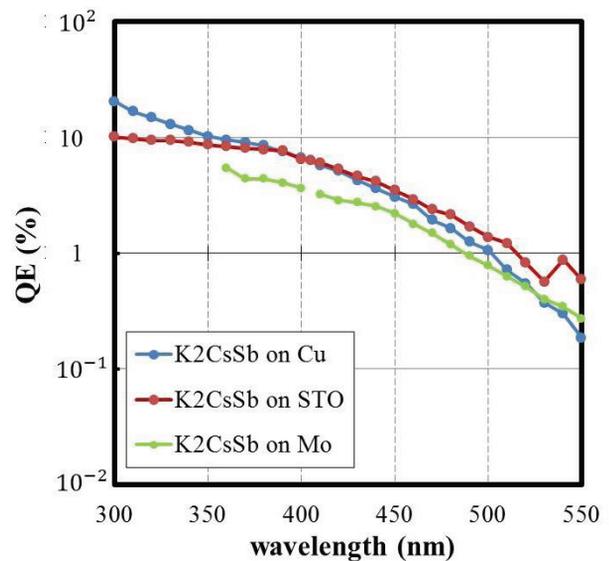


Figure 4: Wavelength dependence of QE.

## SUMMARY AND FUTURE WORK

We achieved the high quantum efficiency with three kinds of substrates and to confirm the electron emission by back-illumination. Recently, we started to measure the critical magnetic field by SQUID and the emittance of photocathode under low temperature. In the future, we will deposit  $\text{K}_2\text{CsSb}$  on LTO and incorporate into superconducting RF cavity.

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