JAEA PHOTOCATHODE DC-GUN FOR AN ERL INJECTOR

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Abstract

An ERL-based next-generation synchrotron light source and free electron laser require an electron beam of large current and small emittance. In order to realize an electron gun satisfying such requirements, we are developing an NEA-GaAs photocathode DC-gun. The gun is based on an existing DC-gun of Japan Atomic Energy Agency (JAEA) ERL-FEL and designed to provide a beam with energy of 250 keV and average current of 50 mA. Conditioning of a high voltage power supply has been completed up to design the target voltage of 250 kV. We have also decided to use superlattice semiconductor as a new type of photocathode with higher performance than an existing technology. We fabricated bulk-AlGaAs photocathode samples by molecular beam epitaxy in order to optimize the superlattice structure. We measured quantum efficiency and lifetime of the samples and achieved twice QE of a bulk-GaAs photocathode and longer NEA surface life than that of the bulk-GaAs photocathode.

INTRODUCTION

NEA-GaAs photocathodes have played very important roles as polarized electron sources in several fields of fundamental science [1]- [5], because polarized electrons is generated from an NEA-GaAs photocathode can be through the excitation of electrons by polarized photons tuned to the band-gap energy.

Now, an NEA-GaAs photocathode is also expected as a high-brightness electron source for ERL-based next-generation synchrotron X-ray light sources (ERL-LS). Ultimately high-brightness electron beam is required to realize the ERL-LS [6]. In order to realize such a high-brightness electron source, we need to control initial momentum spread of electrons as small as possible. An NEA photocathode can generate electron beam with such small initial momentum spread by excitation energy corresponding to the band-gap.

However, a conventional NEA-GaAs photocathode using a bulk type of GaAs semiconductor (bulk-GaAs) has serious problems, small quantum efficiency (QE) and short lifetime of the NEA surface.

In JAEA, we are developing a high-brightness electron gun for future ERL LS and FEL. In this study, we have decided to use a superlattice semiconductor for a high-brightness photocathode to fulfill the requirement of future ERL LSs. In the design of superlattice structure, we can optimize its electron affinity, band-gap energy and quantum confinement effect to improve the photocathode performance: higher QE, smaller momentum spread and longer lifetime.

DEVELOPMENTAL STATUS OF THE JAEA PHOTOCATHODE DC-GUN

An NEA photocathode has a fragile surface consisting of thin layer of cesium-atoms attached to gallium-atoms, which form electric dipole field to pull down the vacuum potential barrier. The NEA surface is easy to destroy by ion back-bombardment, which is ion generation by collision of extracted electrons and residual gas molecules followed by acceleration of the ions toward the cathode surface. Therefore, extreme high vacuum is essential to make an NEA surface of good quality and preserve it for long time.

A field emitting electrons also causes the ion back-bombardment. The field emission current can be suppressed using titanium and molybdenum as electrode materials [7] and isolating gun chamber from NEA activation chamber to prevent cesium contamination to the electrode.

The JAEA photocathode DC-gun consists of the gun chamber, the NEA surface preparation chamber and the load-lock system for transporting photocathode between these chambers. The preparation chamber is equipped with 200l/s NEG pump modules and a 500l/s ion pump. The gun chamber is equipped with 2000l/s NEG pump modules and two ion pumps, 500l/s and 200 l/s.

We have decided to use titanium alloy for the electrodes and these chambers. The titanium alloy shows out-gassing rate of 6×10^{-13} Pa m/s, which is much lower than that of standard vacuum materials by three orders of magnitude [8]. In our estimation of the ultimate pressure using the pumping speed and the out-gassing rate, the chambers is expected to be below 5×10^{-10}Pa

The ceramic insulator of the gun and the high voltage stack of the 250kV-50mA power supply are located side-by-side in a pressure vessel filled with SF6 gas of 2kgf/cm^2.

Figure 1 shows the gun chamber and the high voltage power supply.

Figure 1 : JAEA photocathode DC-gun.

Conditioning of the high voltage power supply has been completed up to the design voltage of 250kV. Figure 2 shows leakage current of high-voltage terminal as a function of applied voltage. We confirmed the linear relationship between leakage current and supplying voltage without severe corona discharge.

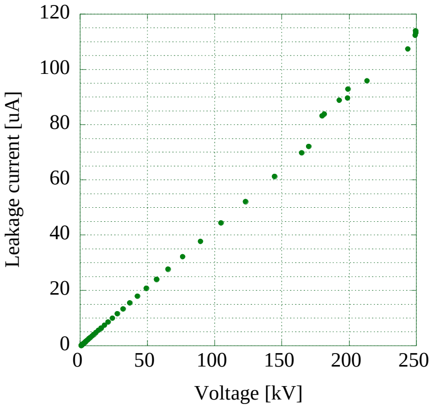

Figure 2: Leakage current of the high-voltage terminal as a function of applied.

STRATEGY OF A NEW TYPE OF PHOTOCATHODE

Superlattice photocathode

We have decided to use a superlattice photocathode as a new type of photocathode with higher performance than the existing technology [9]. A superlattice structure has periodically interchanging solid layers, well-layer and barrier-layer, thickness of which is less than 10nm. By selecting appropriate semiconductor for a each layer, a superlattice is possible to have larger band-gap energy and smaller electron affinity than that of a bulk-GaAs.

We consider the superlattice has intrinsic advantages in realization of higher QE, smaller initial momentum spread of photoelectrons and a longer lifetime of the NEA surface than those of a bulk-GaAs photocathode due to the following two reasons.

(1) Larger band-gap and smaller electron affinity than those of a GaAs is possible by optimization of a superlattice structure.

Experimental results of polarized electron sources have suggested that larger band-gap photocathode is more suitable for higher QE photocathode [10]. Moreover, we predict smaller electron affinity is more suitable for longer NEA life. Because a semiconductor with smaller electron affinity has lower vacuum level when the surface is NEA-activated.

(2) Electron density of state (DOS) for a superlattice is a step function of excitation photon energy because of quantum confinement effect.

In a semiconductor photocathode, QE is proportional to its DOS integrated from the band-gap energy to the excitation photon energy. A bulk GaAs, which has a monotonically increasing DOS function, requires rather higher energy photons to achieve high-QE operation at the expense of large momentum spread of electrons. A superlattice photocathode, on the other hand, enable one to achieve high-QE and small momentum spread simultaneously by choosing a photon energy just above the step energy of DOS [11].

NEA-ALGAAS PHOTOCATHODE

Advantages of bulk-AlGaAs in a high QE and a longer lifetime

In order to confirm the effect of band-gap energy and electron affinity on the photocathode performance, we have measured QE and lifetime of different materials: bulk GaAs and bulk AlGaAs, which has larger band-gap energy and smaller electron affinity than GaAs. It is known that the AlAs semiconductor has larger band-gap energy and smaller electron affinity than the GaAs semiconductor [12].

The measurement of the QE and the NEA surface lifetime as a function of band-gap energy and electron affinity is essential for optimization of the material fraction in the barrier layer of a superlattice structure. The bulk AlGaAs cathode is also expected to be a higher QE and a longer lifetime in comparison with a conventional GaAs photocathode.

Fabrication of crystal samples

We fabricated bulk-GaAs and bulk-AlGaAs samples with various Al fractions (=0.10, 0.17. 0.28). These samples have the same active-layer thickness for the photoelectron generation. Figure 3 shows samples fabricated by Molecular Beam Epitaxy at Nagoya University.

Exposure of a cathode surface to atmosphere results in adsorption of impurities such as oxide and carbide, which are harmful for NEA activation and hard to remove by heat cleaning. The samples have, therefore, covered by arsenide film in their preparation at the MBE chamber. The film is removed by heating in a vacuum chamber just before the NEA activation.

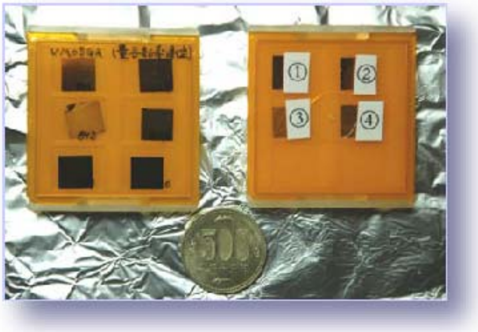

Figure 3: Photocathode samples: bulk-GaAs and bulk-AlGaAs.

Experimental setup

The measurements of QE and life time for GaAs and AlGaAs have been made at a test bench as shown in Figure 4.

The main chamber keeps extreme high vacuum of 3×10^{-9} Pa using the combination of a 500 l/s ion pump and a 1300 l/s NEG pump. The surface of samples is cleaned by radiation heating using a tungsten heater. The NEA surface is activated by alternatively adsorption of cesium and oxygen (yo-yo method).

Ti:Sapphire laser (720-870nm), He-Ne laser (633nm) and laser diode (690nm and 670nm) is used as a excitation laser.

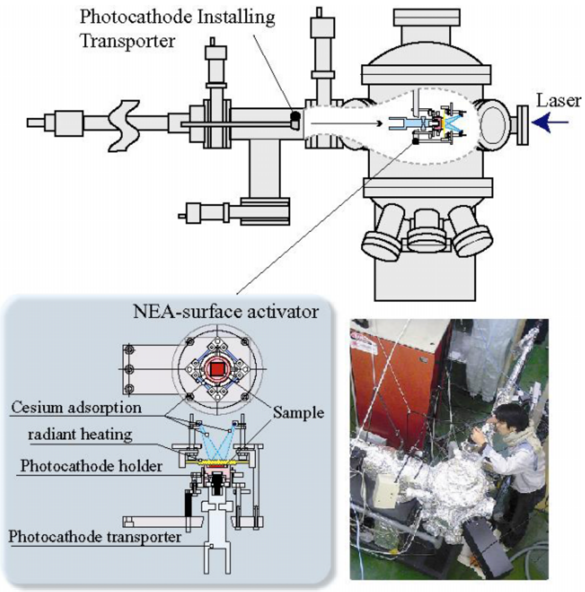

Figure 4: Experimental set up.

Quantum efficiency measurement

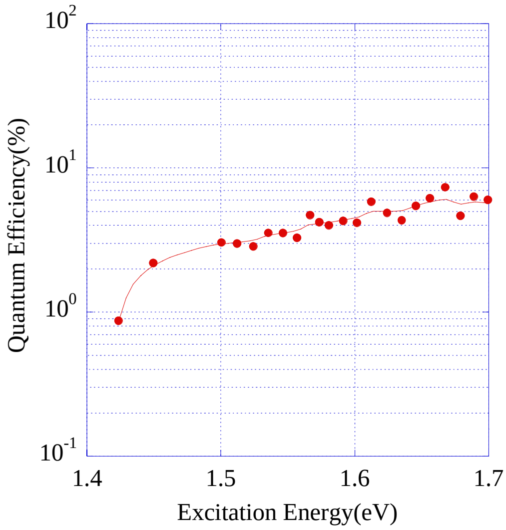

Figure 5: Quantum efficiency of the bulk-GaAs sample

Figure 5 shows measured QE spectrum of the bulk-GaAs sample. We can see a threshold around the band-gap energy (1.42eV) and QE of 2~3% from the band-gap energy to 0.1eV above the band-gap energy. These results are consistent with previous experiments [13].

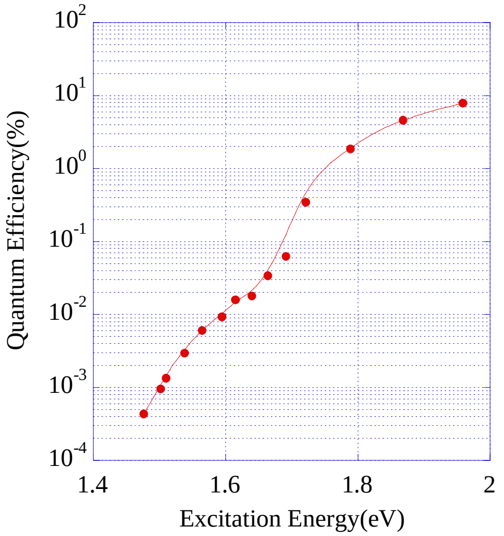

Figure 6: Quantum efficiency of the bulk-AlGaAs sample.

Figure 6 shows QE spectrum of the bulk AlGaAs sample. We can also see a threshold around the band-gap energy (1.79eV) calculated from the content of aluminum.. The QE from the band-gap energy to 0.1eV above the band-gap energy is 5~8%, which is two times higher than that of the bulk-GaAs sample.

NEA-surface life measurement

Figure 7 shows measurement results of NEA surface lifetime of samples, where laser photon energy was chosen at 0.1 eV above the band-gap for each sample. Photocurrent was below 100 nA and applied voltage was as low as 200 V to avoid NEA surface degeneration by ion back bombardment.

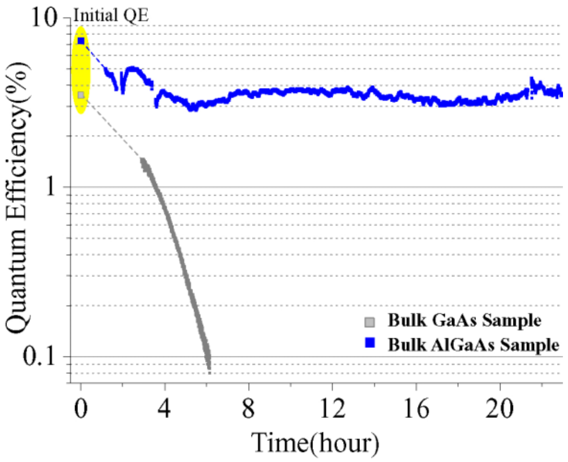

Figure 7: NEA-surface lifetime of bulk-GaAs (laser wavelength of 804nm) and bulk-AlGaAs (laser wavelength of 633nm).

In the case of the bulk-GaAs, QE, initially 3.5%, decreases below 1% 4hours after the NEA activation and the photocurrent ceases after 6 hours. In the case of the bulk-AlGaAs, QE shows initial drop from its initial value of 8% to 3% during 5 hours, but keeps 3% QE more than 26 hours.

From these results, we have found the bulk-AlGaAs has a longer lifetime of NEA surface than the bulk-GaAs. These results agree with our prediction that smaller electron affinity is suitable for longer NEA life.

SUMMARY

In JAEA, we are developing an electron gun for future ERL X-ray light sources and FELs. Fabrication of a DC gun and study on a photocathode for small emittance and high average current are in progress. We have proposed novel approaches, titanium alloy for the DC gun chambers and superlattice for the photocathode. The superlattice produces electrons with small initial momentum spread due to its quantum confinement effect, and realizes high QE, small emittance and long life time by optimizing well- and barrier-layers so that it has large band-gap and small electron affinity. Preliminary results from the measurements of QE and lifetime for the bulk GaAs and the AlGaAs photocathodes support our strategy. We will measure QE and NEA surface of samples with various fraction of aluminum to optimize the superlattice structure

ACKNOWLEDGEMENT

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