Evaluation of Emittance Characteristics of Negative Electron Affinity GaAs-Based Photocathode

To produce a diffraction limited hard X-ray, an Energy Recovery Linac (ERL)-based light source is planned at the High Energy Research Organization. The parameters of the light source such as brilliance and intensity depend on the quality of the electron beam such as emittance, which is a function of the size and angular spread of the electron beam, and current. Therefore, an electron gun which produces low emittance and a high-current beam is needed. To achieve such a beam, we have developed a high-voltage DC gun with GaAs-based photocathode which has a negative electron affinity (NEA) surface condition. With this type of electron source, the emittance depends on the laser wavelength, structure of the photocathode, temperature, and other factors. Therefore, we evaluated the emittance characteristics of GaAs-based photocathodes, namely commercially available bulk GaAs, thickness controlled GaAs (about 120 nm or 1200 nm), and GaAs/GaAsP superlattice.

The electron gun is one of the most important components for an ERL. The target values of the Compact ERL are a normalized emittance of 0.1–1 mm mrad and an average current of 10–100 mA [1]. A DC gun with an NEA photocathode is one candidate for achieving the requirements of the ERL. In the ERL, it is essential to improve the quality of the electron beam generated by the photocathode gun, because the quality of synchrotron radiation strongly depends on it. The requirements for the photocathode are the generation of a low-emittance beam, high quantum efficiency (QE), and fast temporal response of the photoemission, which is important to control the time structure of the electron beam to avoid the emittance growth and a beam halo. The properties of the photocathode can be described by Mean Transverse Energy (MTE), which is related to the initial emittance, and temporal response. To measure these values, we constructed a gun test facility at the PF-AR south experimental hall (Fig. 1).

The time response depends on the thickness of the photocathode; a faster response was obtained with a thinner photocathode [2]. However, the influence of thickness on emittance was not investigated, so we evaluated the effect of cathode thickness for thickness-controlled photocathodes (Fig. 2). We also evaluated photocathodes of superlattice, which is a candidate for a high-current, low-emittance beam [3]. These photocathodes were fabricated by metal organic vapor phase epitaxy at Nagoya University.

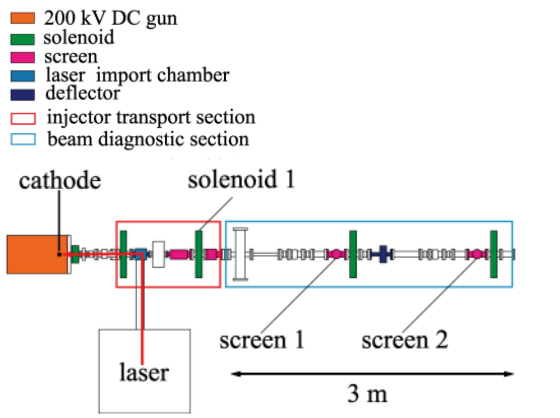

Figure 1
Outline of gun test facility at the PF-AR south experimental hall. Waist scans were executed by solenoid 1 at the positions of screen 1 and screen 2.

On the surface of the photocathode, the normalized rms emittance (ϵ_{nrms}) is given by

$$\epsilon_{\mathrm{nrms}} = \frac{1}{m_e c}\sqrt{\langle x^2\rangle\langle p_x^2\rangle} = \sigma_x\sqrt{\frac{2\langle E_{k_x}\rangle}{m_e c^2}},$$

where x is the transverse electron position, p_x is the momentum, m_e is the rest mass of an electron, and c is the speed of light. The brackets represent the ensemble average of all particles. σ_x is the rms size of irradiated laser, because the spatial distribution of electrons is the same as that of the laser on the surface of the photocathode. Here, $\langle E_{kx}\rangle$ represents the average of the electron transverse energy, therefore, $\langle E_{kx}\rangle$ is called Mean Transverse Energy (MTE).

Of course, the spot size of the laser beam is controllable, but the emittance degradation due to the space charge effect increases with smaller spot size of the laser for the same emission current. Therefore, a smaller value of MTE is desirable. MTE depends on the properties of the cathode material, the cathode structure, the temperature, the excited energy by photons of irradiated laser, and the surface condition. Thus, MTE is an important parameter for describing the cathode's properties.

Electron beam emittance is proportional to the spot size of irradiated laser. We measured the emittance for two laser spot diameters by the waist-scan method at a low emission current so that the space charge effect could be neglected [4]. Figure 3 shows a typical result of the measured emittance. To obtain the MTE, these results were fitted to a line intersecting the origin.

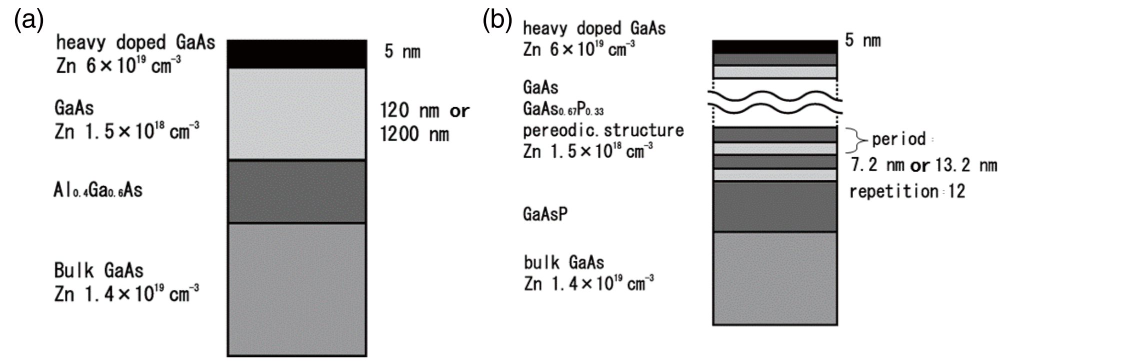

Figure 2
Crystal structure of photocathodes. (a) The samples were controlled to about the thickness of the active layer. (b) The samples have a superlattice structure. Samples SL1 and SL2 had a period of 7.2 nm and 13.2 nm.

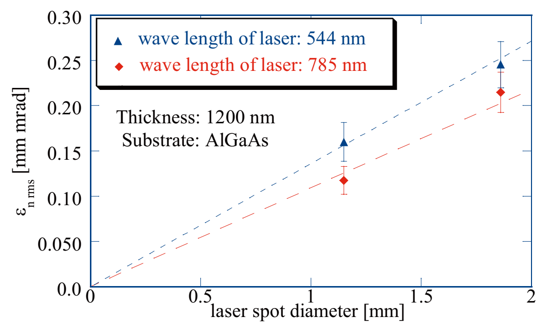

Figure 3
Typical emittance measurement result.

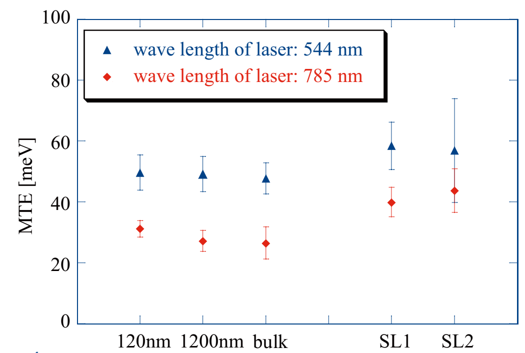

Figure 4
The MTEs of all samples.

Figure 4 shows the measured MTEs at laser wavelengths of 544 and 785 nm. No clear thickness dependence of the MTEs was observed within the error bounds. The green line shows the thermal energy at room temperature. The electrons in the photocathodes are excited, and lose kinetic energy due to some scatterings. Electrons finally reach thermal equilibrium in the photocathode, but the measured MTE does not reach the thermal energy at room temperature (about 12 meV). Furthermore, the emittance of the SL cathodes turned out to be slightly higher than that of the GaAs cathodes, as shown in Fig. 4.

Surface roughness causes changes in the initial direction of emission and distortion of electric field. The surface roughnesses of photocathodes were measured by atomic force microscopy. The roughness of thickness-controlled photocathodes and a superlattice photocathode were 7.3 nm and 33.4 nm rms. These values well explained our results.

These results suggest that the emittance is not affected by changes of thickness within a practical range. On the other hand, the temporal response is sensitive to changes of thickness. The thickness of photocathodes should be selected by considering the temporal response and quantum efficiency. A slightly higher MTE was obtained with the superlattice structure, which may have been due to its rougher surface. Therefore we are continuing to study photocathodes, such as a superlattice structure for a smooth surface, and the characteristics of temporal response of various kinds of photocathodes.

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