Initial Emittance Measurements for Polarized Electron Gun with NEA-GaAs Type Photocathode

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Abstract. Extremely low emittance electron beams are necesarry for new generation accelerators. The value of the required emittances is as low as 0.1 π.mm.mrad. NEA-type photocathodes have an intrinsic advantage for generating such a low emittance beam. In this paper, emittance measuremets of photelectrons extracted from two different NEA phtocahtodes are described. The measurements were carried out using Nagoya University 200kV polarized electron source. The normalized RMS emittances of bulk-GaAs and GaAs-GaAsP superlattice strained photocathodes are as low as 0.12–0.17 ± 0.02 π.mm.mrad and 0.09 ± 0.01 π.mm.mrad with very low charge density, respectively.

Keywords: Thermal emittance; NEA surface; GaAs; Semiconductors; Photoinjector;
PACS: 29.25.Bx;41.85.Qg;

INTRODUCTION

The generation of low emittance electron beams is essential for future accelerator applications. The required emittance for the International Linear Collider (ILC) is lower than 10 π.mm.mrad with a peak currents of higher than 6.4 A at electron injectors [1]. An energy recovery linac design (ERL) require beam emittances of 0.1 π.mm.mrad with four amperes [2]. This is extremely low emittances and very ambitious values.

The Illinois/CEBAF group measured NEA-GaAs emittances at low currents using 100 kV electron source [3]. The emittances were measured as a function of both the laser beam spot size and laser wavelengths using a pair of solenoid lenses and a wire scanner. In this measurement, the result was in the range of 0.5–1.5 π.mm.mrad. The Heidelberg group measured mean transverse energies (MTE) of GaAs photoelectrons as a function of those longitudinal emission energy using a unique method [4]. As results of their measurement, the MTE is shown to be constant and equal to about 25 meV if the vacuum energy (the value of NEA) is maintained at least as high as the conduction band minimum. This minimum MTE gives a thermal emittance of 0.1 π.mm.mrad.

In order to study more details of such advantage of NEA photocathodes, we have made emittance comparison experiments for bulk and SL strained photocathodes. In this paper, we report the emittance measurements of the electron beam emitted from

CP915, *Proceedings of the 17th International Spin Physics Symposium,* edited by K. Imai, T. Murakami, N. Saito, and K. Tanida

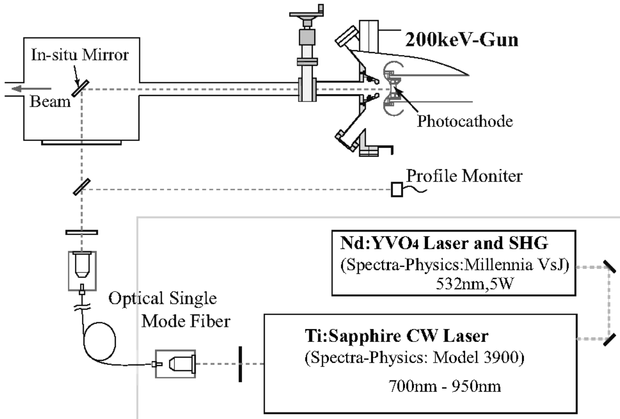

FIGURE 1. Schematic view of laser and transport system

bulk-GaAs and GaAs-GaAsP superlattice (SL) strained photocathodes.

MEASUREMENTS SETUP

Laser system

A Nd:YVO$_4$ pumped Ti:sapphire laser system (720–860 nm) was used as a CW light source. This laser light was transported to the 200kV gun by using a 10 m single mode fiber and illuminated photocathodes in under a small angle of 1.1 degrees, as shown in Fig. 1. The spatial laser profile at the photocathode was well approximated by a Gaussian distribution function with a diameter (one standard deviation) of 0.5 mm.

Pepper pot system

Measurements were carried out using the Nagoya University 200-kV polarized electron source, consisting of an NEA photocathode DC gun and a surface activation chamber with a load lock system, combined with a Mott polarimeter and an emittance measurement system [5]. The extracted voltage was between 120 and 190 kV in the emittance measurements. The vacuum pressure during the gun operation was 2.0×10^{-9} Pa. The base pressure of the emittance measurement chamber was two orders of greater than that in the gun, and a differential pumping chamber with an in-situ mirror for the small angle laser illumination to the photocathode was inserted between the measuremet chamber and the gun. The pepper-pot mask was located 1 m downstream from the photocathode, and there were no electromagnetic bending components between them.

A high-precision pepper-pot method was employed to measure the emittance of an electron beam with an energy range of 100–200 keV. The system consisted of a pepper-pot mask and a scintillation screen. This system was based on the technique of Ref. [6] and modified for a 200-kV gun [7]. In this system, the beamlets passing through the mask pinholes drift and hit the screen located downstream. The position and width of each luminous spot on the screen are observed by a CCD camera. The profile of the beamlets is analyzed from an image averaged over 30 observations to improve the signal-to-noise ratio. The profile is found to be well approximated by a Gaussian distribution function. The beamlett width is defined as two standard deviations of the distribution and is determined from the numerical fit. In our measurements, the uncertainly in the emittance was dominated by the measurement uncertainly of the beamlet width determined from the luminous spot on the scintillator.

Photocathode

bulk-GaAs and GaAs-GaAsP SL strained crystals were used as photocathodes for the emittance measurements. A round bulk-GaAs sample was cut by laser irradiation [8] from a commercially available GaAs wafer with heavy doping (Zn 1.4×10^{19} cm^{-3}). The GaAs-GaAsP SL strained sample was fabricated by metal-oxide chemical-vapor deposition (MOCVD) at Nagoya University. The crystal structure and doping density were selected to achieve high polarization and high quantum efficiency (QE) [9].

The photocathode crystals were heat-cleaned at 450°C for one hour in the activation chamber. Then, small amounts of Cs and NF_3 were introduced to produce NEA surfaces by the "yo-yo" method.

RESULT & DISCUSSION

In order to measure the thermal emittance, the experiments were carried out under a beam condition such that emittance growth by the space charge effect was negligible. For this purpose, the extracted current was suppressed to below 15 nA, which corresponds to a current density of 2 μA/cm^2. The emittance of the GaAs-GaAsP photocathode was measured as a function of the extraction voltage, as shown in Fig. 2, where a laser wavelength of 759 nm was used, shorter than the bandgap wavelength of 770 nm. The emittance exhibits no beam energy dependence and is constant around 0.14 ± 0.02 π.mm.mrad. This confirms that emittance growth by the space charge effect is negligible. Subsequent measurements were carried out using the 120-kV beam with the same current density.

The horizontal normalized rms emittance for the bulk-GaAs sample as a function of the laser wavelength is shown in Fig. 3 (a). Two series of data on bulk-GaAs were taken for different QE conditions; the data points indicated by circles and crosses correspond to surface conditions with QE's of 0.7% and 0.21%, respectively. For a laser wavelength longer than the bandgap wavelength (890nm), the emittances for the both data series are almost constant and gradually increase as the laser wavelength decreases. The minimum emittances were 0.18 ± 0.03 π.mm.mrad and 0.12 ± 0.02 π.mm.mrad.

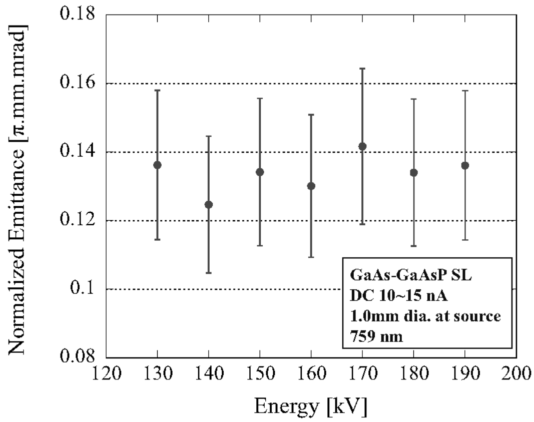

FIGURE 2. Normalized rms emittances as a function of extracted electron energy

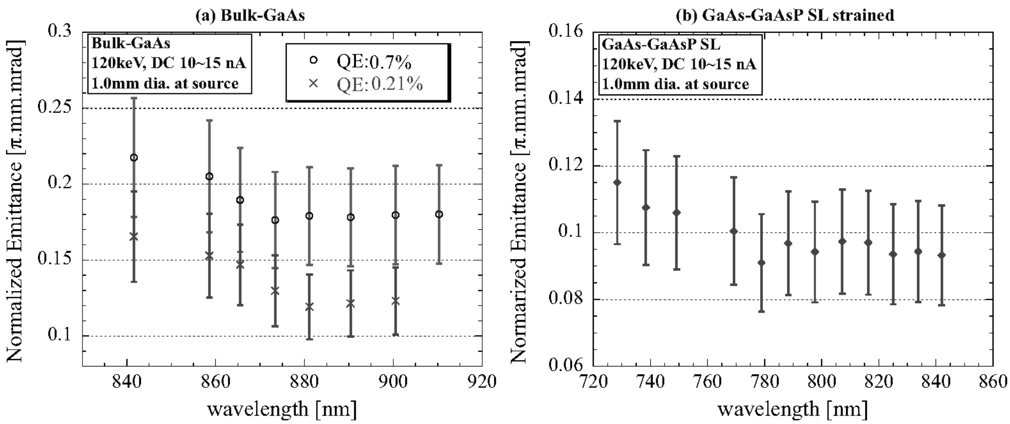

FIGURE 3. Normalized rms emittances as a function of laser wavelengths, (a) and (b) for bulk-GaAs and GaAs-GaAsP SLS, respectively

The same experiment was performed for the GaAs-GaAsP photocathode; the result is shown in Fig. 3 (b).The minimum emittance was 0.096 ± 0.015 π.mm.mrad for a 0.026% QE surface. The laser wavelength dependence has a similar tendency as for the bulk-GaAs result.

Both data sets are plotted in Fig. 4 as a function of the electron kinetic energy. The data points indicated by circles and crosses correspond to bulk-GaAs and those indicated by squares correspond to GaAs-GaAsP. A negative energy means that the laser energy is lower than the bandgap energy. Comparing the emittance growth at energies higher region than the bandgap energy (energy > 0), it is clear that the gradient of the emittance growth for GaAs-GaAsP is lower than that for bulk-GaAs. This difference indicates that a superlattice photocathode produces a lower emittance beam.

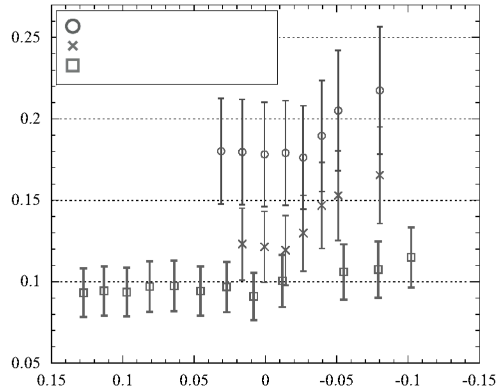

FIGURE 4. Comparison of experimental results, bulk-GaAs and GaAs-GaAsP SL strained for the normalized emittances due to extra electron energy from vacuum level

In the superlattice layers there are several quantum mini-bands with band-widths of a few tens of meV. For example, the width of the mini-band of the lowest conduction band for the GaAs-GaAsP layers is 35 meV and the next energy level in the conduction band is 100 meV higher than the lowest band. If the photon energy is chosen to be slightly higher than the bandgap energy, the heavy hole electrons are only excited to the lowest conduction mini-band, and the allowed kinetic energy range of the excited electrons is limited within a few tens of meV. Due to this limitation, the gradient of the emittance growth for a superlattice photocathode is suppressed to be lower than that of bulk-GaAs.

CONCLUSION

We measured the thermal emittance of two kinds of NEA-GaAs type photocathodes using a high-precision pepper-pot technique. In order to suppress the emittance growth caused by the space charge effect, the measurements were carried out with low current density beams. The predicted lowest emittance of 0.1 π.mm.mrad was confirmed by this experiment and thermal emittance growth was observed with increaseing laser photon energy.

It is first demonstrated that superlattice photocathodes have the advantage for suppressing the emittance growth for higher photo-excitation energies by comparing the data for the bulk-GaAs and GaAs-GaAsP photocathodes It has also been confirmed by previous experiments that superlattice photocathodes suppress the photovoltage effect for high current density beam generation [10, 11]. These two advantages show that NEA superlattice photocathodes can simultaneously realize the high peak and low emittance beams for future accelerators.

As a final remark, further studies are required for designing a high gradient gun and an optimized laser system for space charge effect compensation to produce a practical low emittance beam.

ACKNOWLEDGMENTS

This work was supported by a Grant-in-Aid for Scientific Research (Grants No. 15204016) from the Ministry of Education, Culture, Sports, Science and Technology of Japan and a series of research funds from KEK for the cooperative development of low emittance electron sources (2003-2006). Two authors, N.Yamamoto and M.Kuwahara were financially supported by JSPS Research Fellowships for Young Scientists.

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