Production of High Density Polarized Electron Beam from GaAs-GaAsP Superlattice Photocathode

M.Yamamoto[a], N.Yamamoto[a], S.Okumi[a], R.Sakai[a], M.Kuwahara[a], T.Morino[a], K.Tamagaki[a], A.Mano[a], A.Utsu[a], T.Nakanishi[a], C.Bo[b], T.Ujihara[b], Y.Takeda[b], and M.Kuriki[c]

[a]*Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8602 Japan*
[b]*Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan*
[c]*High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki, 305-0801 Japan*

Abstract. Future high energy accelerators require polarized electron sources that can generate high bunch charge and/or high density electron beam with low emittance. Various superlattice photocathodes and a high voltage load-lock DC gun have been developed at Nagoya University for this purpose. Using a GaAs-GaAsP strained superlattice photocathode, the bunch charge of 8nC was extracted in a 1.6ns bunch with a 20 mm diameter, and that of 3.3pC in ~30ps bunch with 1.2mm diameter.

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INTRODUCTION

High intensity (6.4nC in a short <2ns bunch length) and low emittance ($\varepsilon_{n.rms}$<10 π.mm.mrad at a source) polarized electron beam is required for the International Linear Collider (ILC) electron source [1]. A conventional high voltage DC-gun can comply with requirement of current density of several tens mA/mm^2.

In addition, photoemission from a GaAs photocathode with a negative electron affinity (NEA) surface has another advantage of generating the low thermal emittance beam. Therefore the high voltage DC-gun with the NEA-GaAs photocathode is a promising for a next generation light source accelerator such as Energy Recovery Linac (ERL) [2]. However, the requirements for average current (I_{avg}) and peak current density (i) are quite high (I_{avg} ≥10mA, i ≥ several hundreds mA/mm^2) and further R/D is necessary.

It is well-known that the maximum charge density produced from a photocathode is limited by not only space-charge-limit but also surface-charge-limit (SCL) phenomena. The SCL effect is inherent property for the NEA photocathode. This effect becomes significant as the extraction current densities become higher, because the conduction band electrons are accumulated in the surface band bending region. It is confirmed that the superlattice photocathode with modulation p-doping is effective to overcome

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the SCL problem [3,4]. Here we describe the various beam performances obtained by the high voltage load-lock DC gun that had been developed at Nagoya University with a GaAs-GaAsP strained superlattice photocathode [5-7].

EXPERIMENTAL SETUPS

Photocathode fabrication & NEA activation

In order to suppress dark-current from the photocathode edges, a diameter of 23mm round-shaped photocathode was prepared for our load-lock gun.

A substrate of the photocathode was fabricated from a 2-inch p-doped GaAs wafer by laser cutting method as follows. a) The wafer was covered with thin silicon dioxide by sputtering in the vacuum to protect the surface from contaminants. b) Paraffin was used for fixing the wafer on a stage and then laser-cutting was done in an exhausted box. c) Paraffin on the substrate was removed by diethyl ether and rinsed by acetone and ethanol in an ultra sonic bath. e) The silicon dioxide layer was removed by hydrogen fluoride acid.

A superlattice structure was grown on this substrate by MOCVD method. First, a 2-μm-thick $GaAs_{0.64}P_{0.36}$ buffer layer was grown on the GaAs substrate. A superlattice structure of 12 pairs of GaAs well layer and $GaAs_{0.64}P_{0.36}$ barrier (4nm each thickness) was grown on the buffer layer. The Zn doping concentrations were chosen to be $1.5x10^{18}cm^{-3}$ and $6x10^{19}cm^{-3}$ in the interior of superlattice and in the 5-nm-thick GaAs surface layer, respectively.

This round-shaped GaAs-GaAsP photocathode was installed in a preparation chamber and heat-cleaned at temperature of ~500°C for one hour. After cooling down for 2 hours, NEA activation was started by alternative deposition of Cs and oxygen onto the surface.

High voltage load-lock DC gun

The activated photocathode was transferred to the gun by 2m-long magnetic manipulator. The vacuum pressure of $1.3x10^{-9}$Pa was obtained by extractor ion gauge in the gun chamber. In order to keep dark current below 10nA for long time, the field gradient on the photocathode was set to be 2.25MV/m (at bias voltage of 150kV) in this experiment. The extracted electron beam was dumped at the end of differential pumping system (about 1m downstream from the gun). The total extracted current was measured through a returning current from ground to the high voltage power supply that was electrically insulated from the ground.

A higher bias voltage more than 200kV is required for production of short bunched beam with low emittance. For this purpose, a plan to replace the present SUS electrode by new one with molybdenum cathode and a titanium anode has been in progress [8].

1.6ns & 25ps Laser Systems

For the ILC micro-pulse generation, a Ti:Sapphire laser system pumped by Q-switch mode of Nd:YAG was used. The initial laser pulse with ~20ns (FWHM) length was sliced to be shorter than 2ns pulse using a combination of a fast pockels-cell and a polarized beam splitter. The sliced laser pulse was then transmitted to a gun optical system using a 30m-long multi-mode optical fiber with a core diameter of 220μm and a numerical aperture of 0.22.

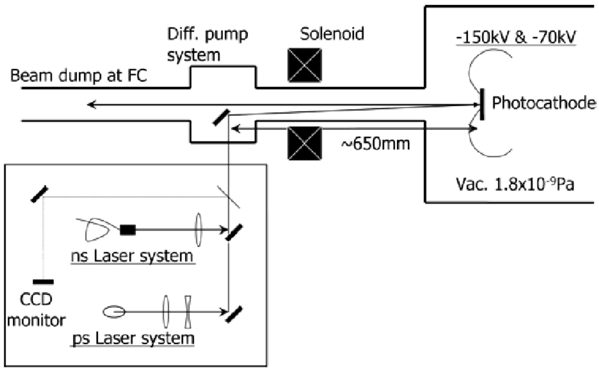

FIGURE 1. A gun optical system and geometries between the photocathode and other components.

A set-up of gun optical system is shown in Fig.1. The incidence maximum laser pulse energy was limited to be less than 10μJ/pulse to prevent the damage of an end face of optical fiber. The laser spot profile was measured by a CCD camera placed on the optical stage with the same distance to the photocathode. The laser pulse length of ~1.6ns and spot size diameter of ~20mm (a full emission size of the photocathode) were used for this experiment (Fig.2). The laser pulse was injected into the vacuum and then reflected toward the photocathode with incidence angle of ~1°.

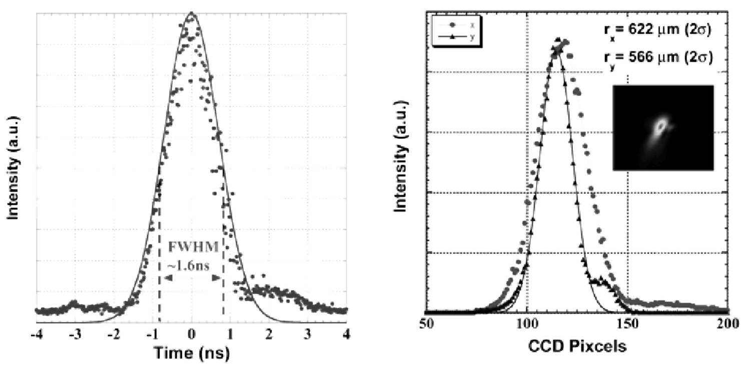

FIGURE 2. Result of nanosecond laser pulse length measurement using PIN-photodiode (left), and spot size measurement of picosecond laser pulse by CCD camera (right).

The other experiment for picoseconds bunch generation was done using a mode-locked Ti:Sapphire laser system. It produced the laser pulses with the maximum average power of 450mW (5.5nJ/pulse), the length of 25ps (FWHM), and the spot radius of σ_x=622μm, σ_y= 566μm on the photocathode.

Experimental Results

Using 1.6ns laser pulses, a bunch charge of > 8nC was produced from the GaAs-GaAsP superlattice photocathode (quantum efficiency of 2.2×10^{-3} at 780nm). At bias voltage of 70kV, a charge limit effect appeared for a bunch charge with larger than 6nC. At bias voltage of 150kV, the bunch charge of 8nC was extracted without charge limit effect. Comparing both results, it is concluded that the charge limit effect at 70kV was caused by not SCL but space-charge-limit effect.

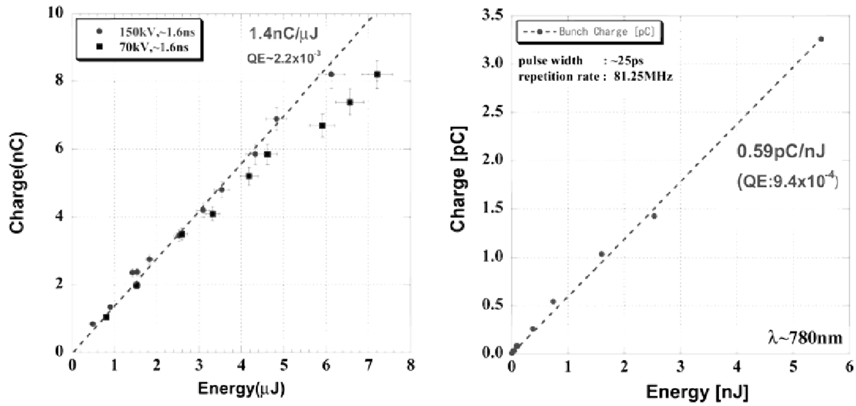

FIGURE 3. The data of laser energy versus extracted charge from GaAs-GaAsP superlattice using a laser pulse length of 1.6ns (left), and 25ps (right).

Using 25ps laser pulses, the extracted current from the GaAs-GaAsP photocathode increased linearly up to 5.5nJ/pulse laser energy at 150kV bias voltage. The peak current density was estimated to be ~180mA/mm^2, where an extracted bunch length was estimated to be ~30ps using Mainz data [9] with parameters of the superlattice layer thickness of 100nm and laser pulse length of 25ps.

This GaAs-GaAsP photocathode could suppress the SCL effect and allowed the current density in excess of ILC requirement. This data shows also the possibility of generating higher current density than several hundreds mA/mm^2 without the SCL effect.

EMITTANCE SIMULATION FOR 200KV GUN

A beam trajectory simulation of nanoseconds bunch generation was done using General Particle Tracer (GPT) code. The field map along the beam line (static electric field of the electrodes and magnetic field of a solenoid) was made using POISSON code, where the solenoid was placed 15 cm downstream from the photocathode. The simulation results was obtained assuming that 500 macro-particles with cylindrically symmetric space-charge distribution are contained in one bunch, and the normalized rms emittance at 50 cm downstream from the photocathode is minimized by optimizing the solenoid magnetic field.

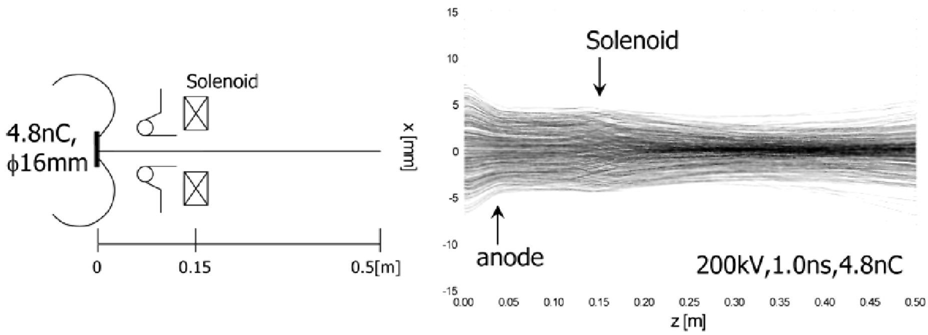

FIGURE 4. The geometry of the electrodes and solenoid (left), and the beam trajectory of the initial parameter for 4.8nC in 1.0ns with bias voltage of -200kV (right).

The initial bunch parameters were chosen for an emission area of ϕ16mm, bunch charge of 4.8nC and 0.7-2.0ns bunch length. For example, the normalized rms emittance of 9.7 π.mm.mrad and rms energy spread of 2.2keV were obtained for the initial bunch length of 1.0ns, as shown in Fig.4 (right).

CONCLUSION

The high voltage load-lock gun was stably operated at 150kV using a round-shaped GaAs-GaAsP strained superlattice photocathode with a diameter of 23mm. A bunch charge of 8nC in 1.6ns laser pulse, 3.3pC by a 25ps laser pulse can be produced without any charge limits. This GaAs-GaAsP strained superlattice with a heavily p-doped surface can generate high density polarized electron beam with more than 180mA/mm^2 without SCL effect.

The simulations of the beam emittance and energy spread for ILC single bunch beam from the 200kV gun were done. For the beam with 4.8nC in 1.0ns bunch, the emittance less than 10 π.mm.mrad was obtained at gun exit for -200kV cathode voltage.

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REFERENCES

1. Strawman BCD http://lcdev.kek.jp/GDE/StrawBCD/
2. S.M.Gruner and M.Tigner, eds., CHESS Technical Memo 01-003, JLAB-ACT-01-04 (2001)
3. K. Togawa et al., Nucl. Instr. Meth. A455 (2000) 118-122
4. J. E. Clendenin et al., Nucl. Instr. Meth. A536 (2005)308-311
5. K. Wada et al., AIP Conference Proceedings, 570, (2001) 1012
6. O. Watanabe et al., AIP Conference Proceedings, 570, 1024 (2001)
7. T. Nishitani et al., J.Appl.Phys. 97, 094907 (2005)
8. F. Furuta et al., Nucl.Instru.Meth A538 (2005) 33-44
9. P.Hartmann et al., Nucl.Instru.Meth A397 (1996) 15-20