POLARIZED ELECTRON SOURCE USING NEA-GaAs PHOTOCATHODE

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Abstract

The important performance required for PES (Polarized Electron Source) depends on the type of machine and physics experiment. Usually it includes following items; 1) high polarization, 2) high quantum efficiency, 3) high peak current for pulse machines, 4) high average current for CW machines, 5) sub-nanosecond multi-bunch production for future linear colliders, 6) long cathode-lifetime and 7) low emittance. The technologies developed to get the best performances are summarized briefly and the prospects of further R/D works are discussed.

1 INTRODUCTION

Nowadays, polarized electron beam has been widely used for various spin physics experiments at many electron accelerators. The GaAs-PES is considered as an unique solution up to now to satisfy the requirement of high energy accelerators. It is based on a combination of two physical mechanism; a) optical pumping of VB (Valence Band) electrons by circular photon to CB (Conduction Band) with selection of the electron helicity and b) NEA (Negative Electron Affinity) surface to extract polarized electrons into vacuum, as shown in Fig. 1.

The GaAs photo-emitter consists of a thin layer (thickness~100nm) of crystal with special microstructure and a thin NEA surface (thickness~5nm). Various physical processes that arise in this layer and surface determine the important PES performances. In fact, various technologies that can control these phenomena for our purpose have been developed. As a result, the following performances could be achieved; (1) high polarization ≥ 80%, (2) high QE (Quantum Efficiency) ≥ 0.3%, (3) high peak current (≥ 10A), (4) high average current (≥ 0.5mA), (5) long lifetime (≥ several weeks) and (6) sub-ns multi-bunch beam generation for linear colliders.

However, more R/D works on PES are still required to achieve the better performances for more wide applications. For example, it is not yet successful to produce the ultra-short pulse beam with high charge (≤10ps, @1nC/bunch) by the source. The low beam emittance with high charge (for example, $\varepsilon \leq 1\pi$mm·mrad @1nC/bunch) at the source is also not yet realized.

In this report, these successful achievements and further problems are briefly summarized and discussed.

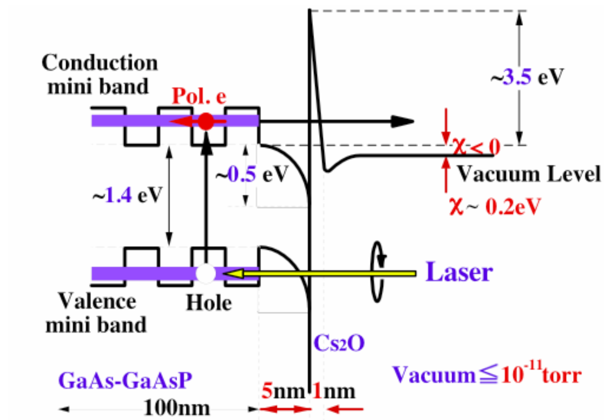

Fig. 1: Polarization and emission mechanism of GaAs-PES with superlattice photocathode

2 HIGH POLARISATION PHOTOCATHODES

In order to produce the highest polarized electrons, the degeneracy between heavy-hole and light-hole band of semiconductor must be removed, and the laser wavelength must be tuned to the band-gap energy so that only the heavy-hole band can be excited. The strained GaAs layer [1] or InGaAs-AlGaAs superlattice [2] has provided such highly polarized (≥ 80%) electron beam for the current electron accelerators. In addition, the GaAs-GaAsP superlattice photocathode has been also developed by Nagoya group [3], and high polarization (~90%) and high QE (~0.5%) are obtained. An example data is shown in Fig. 2, where the maximum polarization is obtained at the laser wavelength of ~780nm.

3 DARK CURRENT AND LIFETIME OF NEA SURFACE

The most important technology for reliable PES operation is preservation of NEA-state that is indispensable to extract polarized electrons from the GaAs-photocathode. A combination of the surface band-bending (BB) by heavily p-doping and the Ga(+)-Cs(-) dipole layer made by deposing Cs and oxygen to the GaAs surface changes the electron affinity from positive (~4eV) to negative (~ –0.2eV). This NEA surface makes possible for highly polarized electrons excited from heavy-hole band to the bottom of CB to be emitted into vacuum.

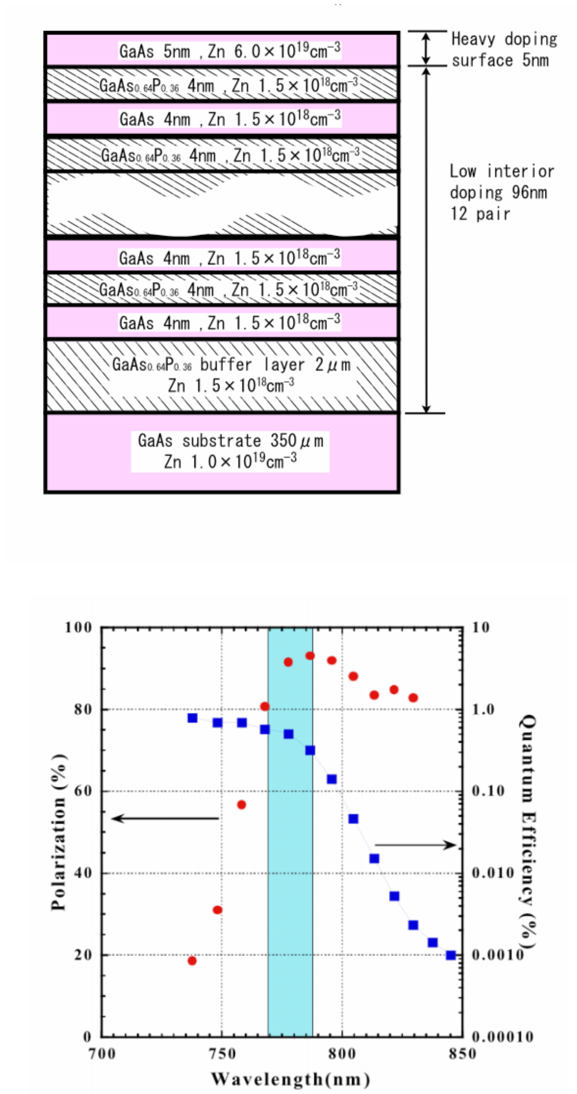

Fig. 2: Microstructure (above) and laser wavelength dependence of polarization and QE (below) of GaAs-GaAsP superlattice (SLSP#16)

As the NEA state is realized by only a few mono-layers of atomic-structure dipole, it is easily degraded or destroyed by (1) adsorption of impurity atoms and (2) back-bombardment of positive ions produced by collision of electron beam itself with residual gas molecules, as shown in Fig. 3.

This lifetime problem can be relaxed by keeping the gun chamber at UHV (Ultra-High-Vacuum) as good as 10^{-11} torr. In addition, the out-gas produced by the field emission dark current from the high-voltage electrodes must be negligibly small. From many experiences of PES operation, it turns out that the total dark current level below 10nA does not cause the serious NEA-degradation. [3]

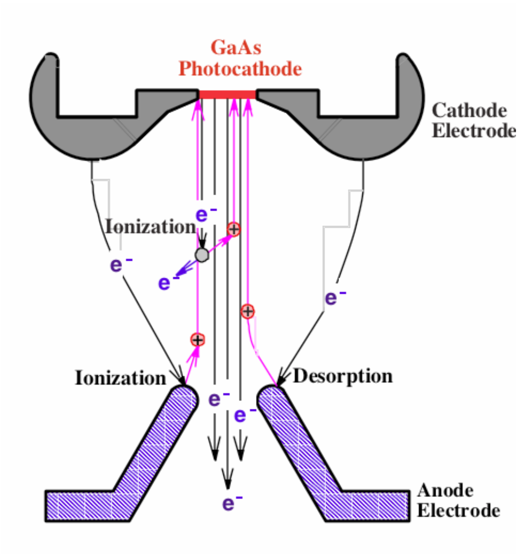

Fig. 3: Mechanism of degradation of NEA surface by ion back-bombardment

4 PEAK CURRENT LIMITATION BY SURFACE-CHARGE-LIMIT

As the BB technology is used to realize the NEA state, the maximum peak current emitted from NEA-GaAs surface is limited not by space-charge limit effect, but by so called SCL (Surface-Charge Limit) effect. It is known that the tunneling probability for CB electrons through NEA-surface into vacuum is usually not higher than 10~20%, and a sizable number of electrons are trapped in the BB region. This surface-charge causes the temporal decrease of BB, although it comes back soon to the initial BB, because the trapped electrons annihilate with the VB holes. However, the SCL effect becomes significant if the accumulation rate of surface-charge becomes faster than the recombination rate, as the decrease of BB is maintained for long time. This effect can be observed clearly for the highly charged double-bunch beam generation, where the second-bunch charge is much smaller than that of the first bunch.

Two kinds of solution were found to relax the SCL effect. One is to make the narrower BB region by heavily p-doping ($\geq 10^{19}$/cc) so that the VB-holes can recombine faster with surface CB electrons. Another is to use the superlattice photocathode. In the GaAs layer of superlattice structure, the energy level of CB-electrons shifts upward and that of VB-holes shifts downward compared with the original energy levels of GaAs. The former shift can increase the electron escape-probability into vacuum and thus decrease the accumulation rate of surface-charge and the latter shift can increase the recombination rate with holes, as shown in Fig. 4.

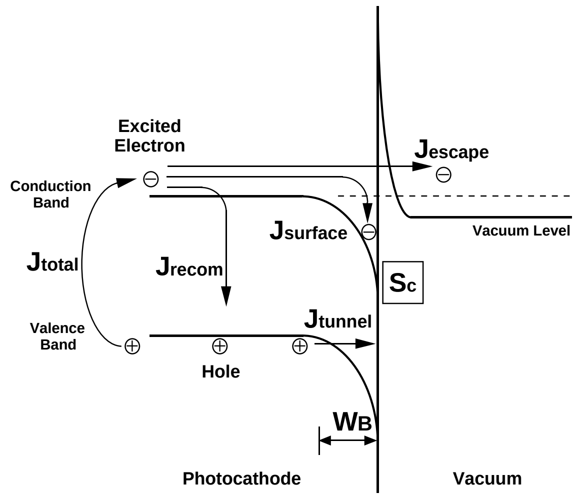

Fig. 4: Tunneling of CB electrons into vacuum and recombination of trapped electrons with VB holes in superlattice photocathode

This excellent property of superlattice photocathode was already demonstrated by experiments [5]. For example, the GaAs-GaAsP superlattice cathode (SLSP#7) installed in a 50keV gun and illuminated by a 0.7ns double-bunch laser (λ=773nm) with 2.8ns separation could produce the clean double-bunch electron beam with polarization of 80% and the maximum bunch charge of 6×10^9 electrons, as shown in Fig. 5. Following the increase of laser pulse power, both of electron pulses grew up to the space-charge limit containing the same charge.

By using the heavily-doped superlattice cathode, the SCL effect should be overcome for the polarized beam with peak-current of 10A in sub-nanosecond bunch. The above multi-bunch beam performances can already fulfill the most of specifications required by future electron-positron colliders.

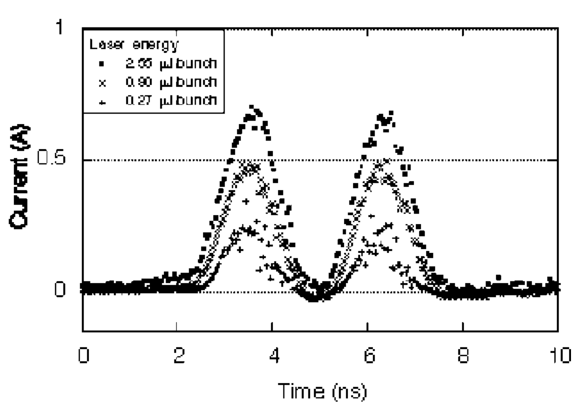

Fig. 5: Time profile of double-bunch electron beam produced by superlattice photocathode

5 THERMAL EMITTANCE OF NEA-PHOTOEMITTER

The thermal emittance (ε_{th}) is defined as the mean transverse momentum of electrons emitted from the cathode surface multiplied by source radius. Although it is not easy, Heidelberg group could measure the mean transverse energy <MTE> as a function of mean longitudinal energy <MLE> for electrons emitted from NEA-GaAs surface [6], as shown in Fig. 6.

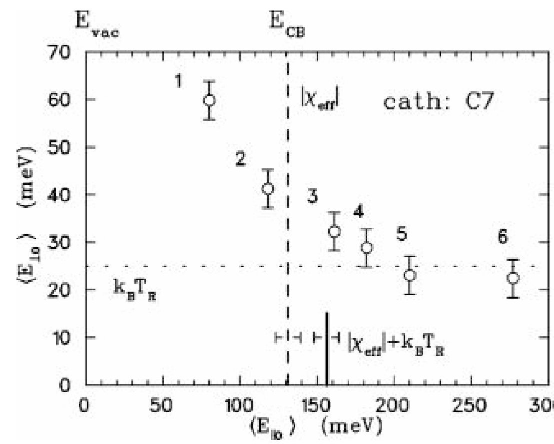

Fig. 6: Mean transverse energy as a function of longitudinal energy of emitted electrons from the NEA-GaAs photocathode (from Heidelberg data)

This data shows clearly that the <MTE> is nearly constant (~25meV, similar to the lattice temperature) for hot (higher energy) electrons which undergo no scattering in BB region. On the other hand, the <MTE> becomes slightly larger for low-energy electrons that undergo the scattering in BB region but finally can escape into vacuum through the NEA surface. Using this <MTE> value , the ε_{th} is estimated to be $\sim0.1\times10^{-6}$ πm/mm-radius by a formula $(r/2)\times$ RT(kTe/mc^2). This emittance value is really small, compared with those of other electron sources, and demonstrates in principle that the NEA-cathode is useful to produce the low emittance beam [7].

However, the overall source-emittance depends also on the space charge effect inside the gun chamber and the higher field gradient is required to reduce this effect. Therefore the NEA lifetime problem described in section 3 becomes more severe, and it is not easy to realize the emittance of $\sim0.1\times10^{-6}$ πm/mm-radius.

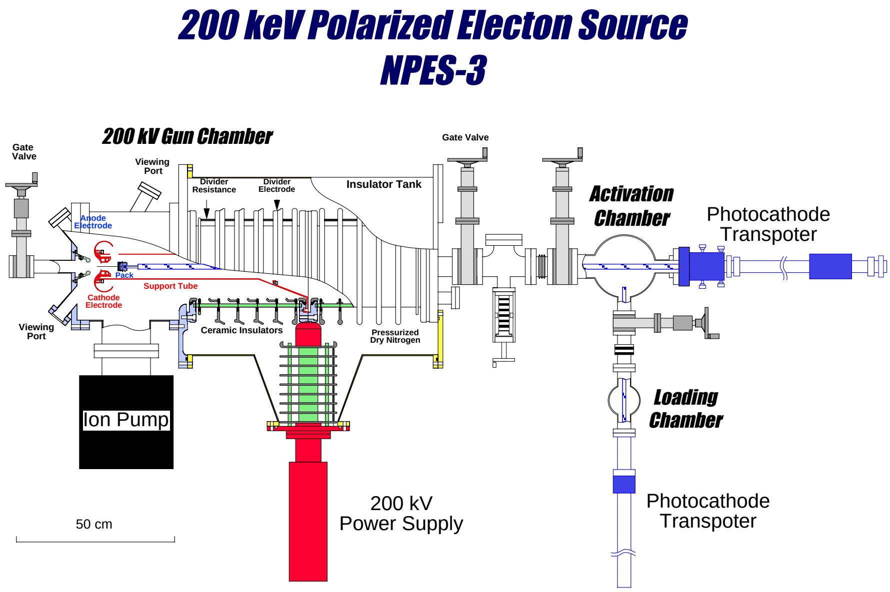

Fig. 7: A schematic view of 200keV polarized electron gun assembly

6 HIGH-GRADIENT POLARIZED DC-GUN

In order to improve the source-emittance by reducing the space charge effect, a 200keV polarized gun with cathode surface voltage of 3.0MV/m has been build at Nagoya University. The normalized source-emittance (ε_n) of 1.0×10^{-6} πm/mm-radius is expected for 3A peak-current by simulation.

The gun system consists of three chambers (gun, activation and loading) and the cathode pad is transferred using by two load-lock systems, as shown in Fig. 7.

The loading chamber has a function of atomic cleaning of GaAs surface. The dark current could be suppressed below 1nA at the bias voltage of 200kV, by using the clean stainless-steel electrodes. The test of NEA-lifetime is now in progress, and the details of this system are given by the separate report in this proceedings [8].

Although it is not the polarized gun, a more ambitious high gradient DC-gun using an NEA-GaAs photocathode with a bias voltage more than 500kV is designed for a future ERL(Energy Recovery Linac) project at Cornell / J-lab. and also at KEK. The aimed source-emittance is an order of 0.1×10^{-6} πm for beam current $\geq$1mA.

However, it is not easy to realize such a gun, as the dark current must be still below ~10nA for such high field gradient ($\geq$10MV/m) to preserve the NEA surface. Therefore it is important to establish the technology to reduce the dark current from metal surface. A new data was taken at KEK, which shows clearly that the titanium is much better than stainless-steel or copper. In Fig. 8, the comparison of dark-current from stainless-steel, copper [9] and titanium is given, and it shows the 1nA dark current level can be realized up to 100MV/m field gradient by titanium electrode. The details of these experimental apparatus and results are given in the separate report in this proceedings [10].

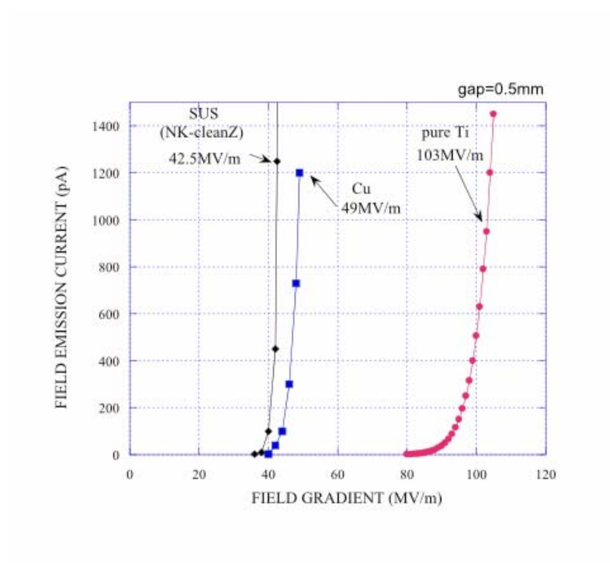

Fig. 8: Comparison of dark-current from stainless-steel, copper and titanium

7 POLARIZED RF-GUN

As well known, higher field gradient ($\geq$100MV/m) can be obtained by the RF-gun, and the preliminary test experiment was performed at Novosibirsk using the NEA-GaAs photocathode. Their data showed the QE of NEA-GaAs cathode fell down quickly when the RF-pulse was applied to cavity. It is obviously due to the severe conditions (relatively poor vacuum, electron back-bombardment, large dark current etc.) in the RF-cavity for NEA surface, and this data suggests the difficulty to realize a polarized RF-gun using the NEA cathode.

In order to overcome the NEA-lifetime problem in RF-guns, a new idea of two-photon excitation-PES was introduced by Nagoya group at the first polarized RF-gun workshop held in April,2001 at FNAL. This method has two advantages, as shown in Fig. 9, those are (1) two-photon absorption can give enough energy to CB electrons to escape into vacuum through the low PEA surface. (It means the NEA is not necessary!), and (2) Even the bulk-GaAs can give the highest electron polarization, because two photons can be absorbed only by the electrons in heavy hole band.

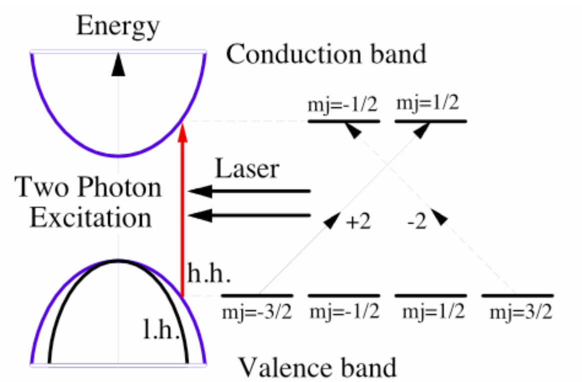

Fig. 9: Polarization mechanism using the two-photon excitation.

The 95% polarization of CB electrons produced in this method was already confirmed by the circular polarization measurement of PL (Photo-Luminescence) [11]. From the difference of both PL spectra with right-hand and left-hand polarity, the circular polarization (Pl) can be estimated, as shown in Fig. 10. The polarization of CB electrons could be also estimated by using the data of this Pl value and spin relaxation time, and it turned out to be 95%. A preliminary measurement of polarization of extracted electrons from a 70keV gun gave also the hopeful result.

In order to enhance the two-photon absorption, the strong laser photon density is required, but it is not the serious handicap, because the high intensity femto-or pico-second laser is used for most of the RF-gun. In answer to needs of future linear colliders or low emittance electron source, further studies are required for development of polarized RF-guns

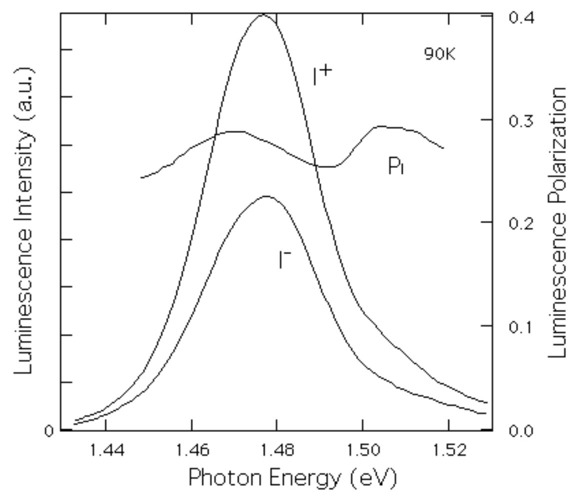

Fig. 10: The circular polarization measurement of photoluminescence for the bulk-GaAs excited by two photons

8 CONCLUSIONS

Various special technologies have been developed to obtain the best performances of polarized NEA-GaAs photoemitter, such as polarization, QE, lifetime, resistance against surface-charge effect and source-emittance. At the same time, the deep understandings for the complex physical phenomena arise inside and surface region of NEA cathode have been required. At moment, studies of polarized-gun-system that can produce low emittance electron beam seem to be urgently required and efforts to find the best solution against some severe problems must be continued.

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