High Polarization and High Quantum Efficiency Cathode Research for Electron-Positron Linear Colliders

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Abstract

The new generation of photocathode for polarized electron source based on the photoemission from semiconductors have been developed to realize much higher degree of ESP(electron spin polarization) than 50% and also the large QE(quantum efficiency) such as 1%. The present performances of those cathodes are reviewed, and the possibilities for further improvements are discussed.

Introduction

In recent years, polarized electron beam becomes to play the very active parts in both of particle and nuclear physics. It is also expected that the polarized e^- beam makes an essential role in the future e^+e^- linear colliders, such as JLC and NLC. In answer to such needs, JLC Polarization group has developed two different types photocathodes of strained GaAs and superlattice to obtain both of high polarization and high quantum efficiency. The present performances obtained by various photocathodes are summarized in fig. 1, where they are plotted for two parameters of polarization and quantum efficiency. The breakthroughs against 50% ESP limit of GaAs came in 1991, and 71% by AlGaAs-GaAs superlattice at KEK/Nagoya/NEC [1], 71% by strained InGaAs at SLAC [2] and 86% by strained GaAs at Nagoya [3] were obtained independently. Then, further improved cathodes have been made based on new ideas, which are called as the second generation of PES cathodes.

Polarization Improvements

For overcoming the 50% ESP limit, the degeneracy at Γ point must be removed. We developed strained GaAs, strained layer superlattice for obtain the higher ESP than 80%.

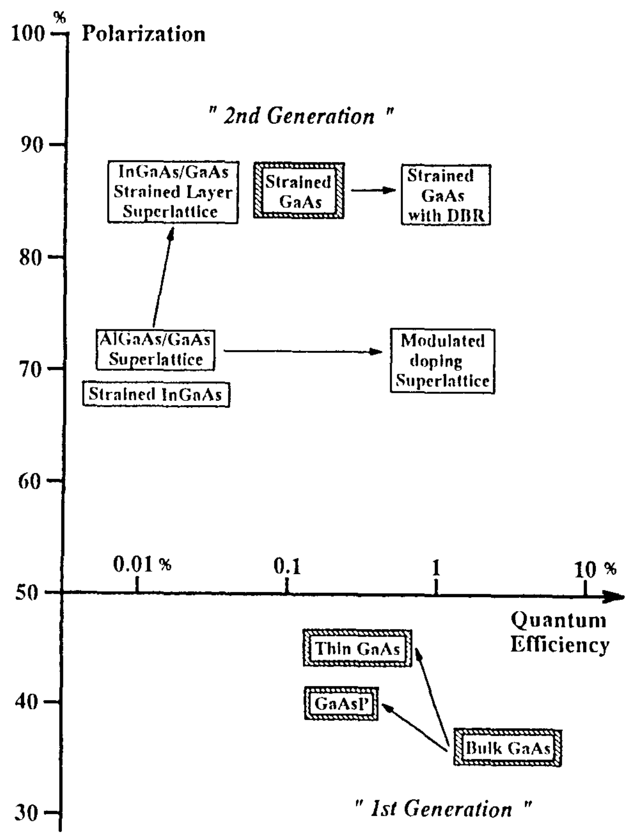

Fig. 1 : Present Status of Photocathode Performances

[Strained GaAs]

The detailed study to understand properties of strained GaAs layer grown on the GaAsP buffer substrate were made experimentally at Nagoya [4] and at SLAC [5]. As results, the ESP higher than 80% with

QE more than 0.1% was routinely achieved by this type of photocathode which was firstly employed at SLC gun in the 1993 run with a large success.

[Strained Layer Superlattice]

The SL(superlattice) is another interesting material to obtain high ESP, since it has more design parameters than strained GaAs. After the first success by GaAs-AlGaAs superlattice which gave the ESP of ~ 70% with QE of 0.01%, various samples were examined by KEK/Nagoya/NEC, and it turned out that there is a limit of the maximum ESP around ~ 75%, probably due to the band-mixing between hh(heavy hole) and lh(light hole) bands.

Thus, a new type of "InGaAs-GaAs strained layer superlattice" was examined just recently at KEK/Nagoya/NEC [6] to overcome this limit. Both types of band splitting between hh and lh bands caused by strain and SL effects may be introduced, because the InGaAs layers are strained, working as wells for both electrons and heavy holes, while the GaAs layers are not strained, working as wells for light holes. For the first sample, In fraction of 15% was chosen, and the energy splitting is estimated to be ~ 30meV, which is defined as a difference between the maximums of hh and lh mini-bands. The maximum ESP of ~ 83% with QE of ~ 0.02% was obtained at laser wavelength of 911nm, as shown in fig. 2. By this success, the advantage of strained layer superlattice is demonstrated and trials for the QE improvements are in progress.

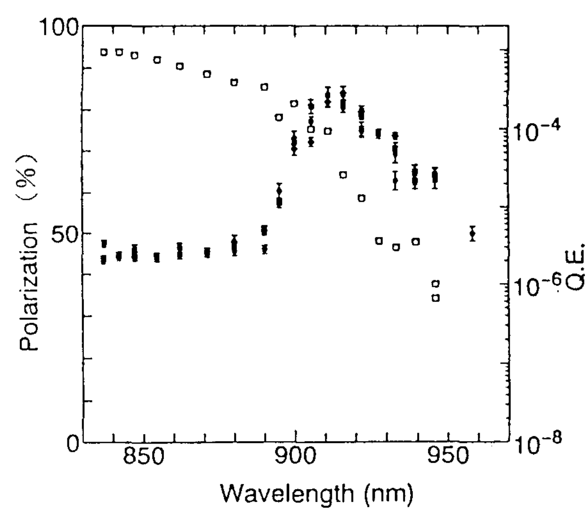

Fig. 2: Q.E. and ESP of photoelectrons from strained layer superlattice

Q. E. Improvements

The photoemission process contains three successive steps, 1) optical absorption, 2) electron transport, and 3) escape across the surface. Therefore the QE is given by a product of three probabilities related to the above steps, and an up-grade of each probability can contribute to the QE improvement. From this viewpoint, the smaller QE of new cathodes compared with normal GaAs has an obvious origin in 1) step. For high polarization cathodes, electrons are allowed to be excited only from the hh band near the band-edge having the small state density.

[Resonant absorption photocathode]

In order to break this limit, the technique of "resonant absorption" was introduced and applied to strained GaAs cathode at Nagoya [7], as shown in fig. 3. Incident laser lights are partially confined in a Fabry-Perot cavity formed by two parallel mirrors ; a quarter-wave DBR(distributed Bragg reflector) and a surface boundary of GaAs and vacuum.

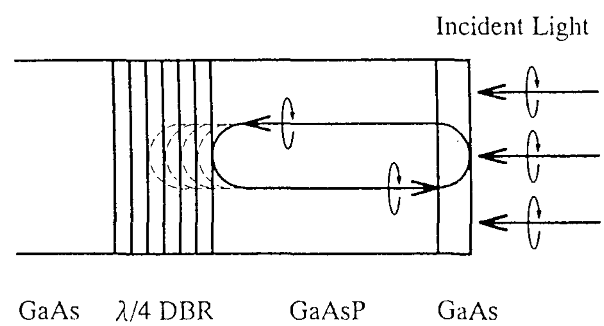

Fig. 3: The principle of resonance-absorption-type strained GaAs photocathode.

The real DBR was composed of 30 pairs of $Al_{0.1}Ga_{0.9}As$ and $Al_{0.6}Ga_{0.4}As$ and had the reflectivity higher than 90% within the laser bandwidth of ~50nm. Significant QE enhancement is expected at the wavelength which satisfy the resonant condition ; $2nL = m\lambda_R$ (m:integer), where n, L are refractive index and total length of optical cavity. The result is shown in fig. 4, where QE of the DBR cathode is indicated by solid circles, while that of normal strained GaAs is done by open circles. The QE of ~1.0% is achieved at wavelength of 866nm which gives the ESP of ~85%. In principle, the same helicity electrons are produced by reflected lights as incident lights, as the photon circular polarization is reversed on reflection and so is the direction of electron emission, and this was also demonstrated by the experiment.

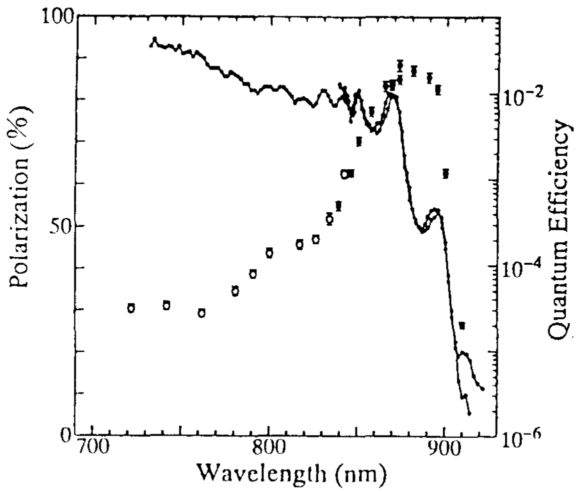

Fig. 4 : Q.E. and ESP of photoelectrons from the resonance-absorption-type strained GaAs.

[Modulated doping superlattice]

Another mechanism for QE improvement for the sample of AlGaAs/GaAs superlattice was found at KEK/Nagoya/NEC [8]. From testing of various samples, it turned out that both ESP and QE dependences on laser wavelength are sensitive to the amount of Be-dopants and the surface structure of superlattice. The typical result is shown in fig. 5, where a shift of polarization dependence on laser wavelength is clearly appeared for two samples. Both samples have the same Be-dopant density of $\sim 5 \times 10^{17}$/cc inside superlattice region, while a high density of $\sim 4 \times 10^{19}$/cc is doped only for a) sample to a 50 Å thick GaAs surface layer. As the shorter wavelength photons can give the much higher QE at threshold of band-gap excitation, this wavelength shift brings a great advantage for QE improvement. The good QE of 0.5% with ESP of $\sim$ 70% at 757 nm was obtained by the a) sample by Nagoya cathode-test-system, and the Q.E. of 2.0% was observed at 752 nm by SLC gun-test-system. This QE difference by a factor of $\sim$ 2 at 752 nm seems to suggest usefulness of a load-lock device which enables cathode insertion into the gun without breaking the vacuum, and avoids deterioration of clean surface during the chamber-baking at (200-300)°C.

[Charge Limit Effect]

By this superlattice cathode, the total charge extracted by SLC gun with a bias voltage of 120 kV was measured and a record performance of 2.3×10^{11} electrons in 2.5 ns was achieved [9]. This is a nice data, because a peak-current from the strained GaAs was limited to $\sim 6 \times 10^{10}$ electrons/bunch by so called "charge limit" effect. This effect appears for production of a ultra-short electron pulse, and seems to be explained that a fraction of electrons arriving to surface get trapped in the band bending region and produce a photovoltage which induces a decrease of the band bending. This effect will be more significant for a multi-bunch pulse which will be used at future e^+e^- linear colliders, and it is an important subject to develop a cathode free from this effect.

In conclusion, various efforts for making the ideal cathode are not yet completed, and there seems to be still enough spaces to require new ideas and/or devises.

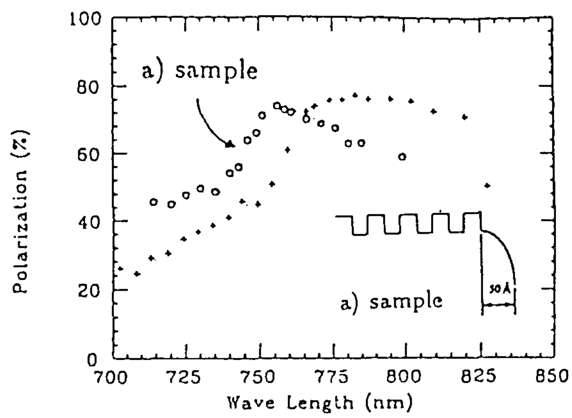

Fig. 5 : A shift of the ESP dependence on laser wavelength, due to the different Be dopings to the AlGaAs/GaAs superlattice cathodes

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