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T. Nakanishi

Department of Physics, Nagoya University, Chikusa-ku, Nagoya-464, Japan

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THE NEW GENERATION OF PHOTOCATHODES FOR POLARIZED ELECTRON SOURCES

Tsutomu NAKANISHI

Department of Physics, Nagoya University, Nagoya-464, Japan

ABSTRACT

The new generation of photocathodes for polarized electron sources based on photoemission from semiconductors has been developed to provide a degree of electron spin polarization much higher than 50% together with a quantum efficiency larger than 1%. The design principles and the measured performances of those cathodes are reviewed, and the possibilities for further improvements are discussed.

1. Semiconductor Photoemission Sources

In recent years, polarized electron beams have become to play an important role in both particle and nuclear physics. Various spin-physics programs that require a polarized e^- beam as an indispensable tool are proposed or have been carried out at several accelerator laboratories such as SLAC, Mainz, MIT-Bates, Bonn, CEBAF, NIKHEF and Novosibirsk. Polarized e^- beams are also expected to play an essential role in the future e^+e^- linear colliders now being studied in Europe, America, Russia and Japan. [1] In answer to these needs, polarized electron source (PES) technology has also been developed intensively. In the following, recent efforts to improve the performance of polarized electron beams produced by photoemission from semiconductors are reviewed. [2, 3]

Historically, various types of gas ionization PES has been studied and developed [4], but at present only the GaAs-type PES is being used in experiments. The GaAs-PES is based on a combination of two fundamental technologies : laser optical pumping and a semiconductor surface with negative electron affinity (NEA), as shown in Fig.1.

GaAs is a semiconductor with a zinc-blende structure, and its orbital wave functions for the conduction and the valence bands have s-state like and p-state like characters, respectively. As a result, the valence band splits into three sub-bands which are assigned by J (total angular momentum) and Jz (its z component). The energy levels of the $J=3/2$ and $J=1/2$ states are separated by the spin-orbit potential; those of four sub-states of $J=3/2$ state are degenerate because of the symmetric structure of the GaAs crystal.

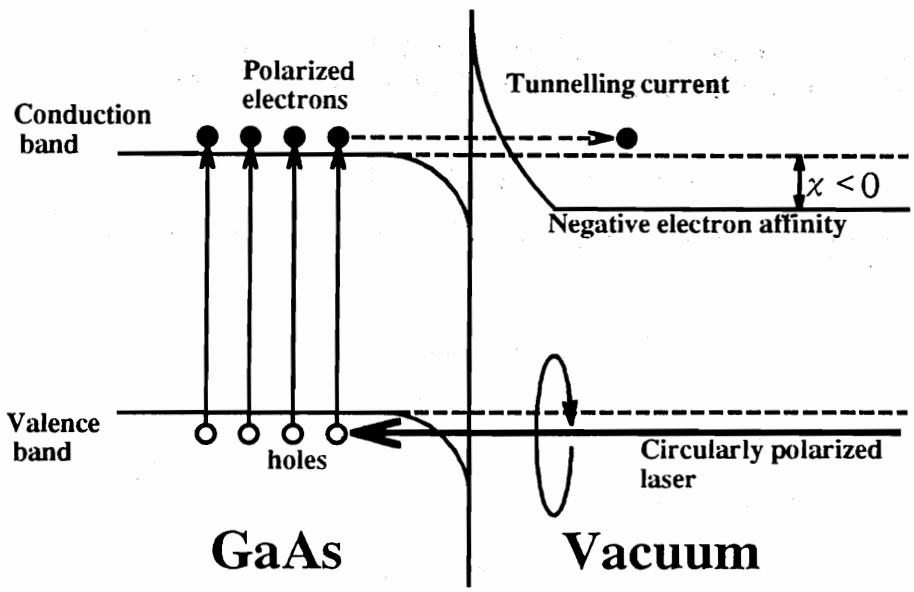

Fig. 1 : Principle of GaAs Polarized Electron Source

The conduction band electrons excited from the Γ point (the top of the valence band) are spin-polarized by means of a selection rule for electric dipole absorption of the circularly polarized photons. The maximum degree of electron spin polarization (ESP) is limited by the fine energy splittings of the band structure in the valence band. It is 50% for normal bulk-GaAs because of the degeneracy between hh (heavy-hole) and lh (light-hole) bands at the Γ point. The ESP improvements to break this 50% limit are discussed in Section 2.

As shown in Fig.2, the excited electron in the conduction band makes many collisions with phonons. At each collision, its direction is changed and a small fraction of its energy is lost, and finally it falls to the bottom of the conduction band. [5] Therefore, the energy level of the vacuum must be lower than that of the bottom of the conduction band, or else the electron cannot be extracted into the vacuum even if it can drift to the surface.

The NEA technique plays an indispensable role in electron emission and it provides much higher quantum efficiency (QE) than do cathodes without NEA surfaces. The NEA surface is made by treating a heavily p-doped GaAs surface with a monolayer of alkali metal and oxidant ($Cs + O_2$ or $Cs + NF_3$). The QE improvements made for the high polarization cathodes are discussed in Section 3.

The NEA surface provides such a great advantage in extracting high peak-current, but it also involves serious technical problems in maintaining a stable source operation, especially at high energy accelerators. For good QE, the NEA surface must be free of adsorbed residual gases (CO_2, H_2O and others) at the sub-monolayer level, which requires careful treatment of the photocathode in ultra high vacuum in the $\sim 10^{-11}$ torr range. The lifetime problem is discussed in Section 4.

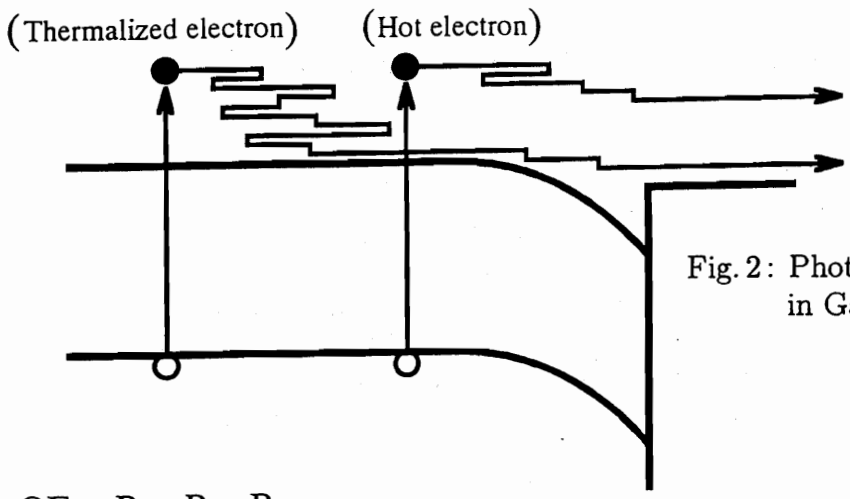

Fig. 2: Photoemission Process in GaAs Photocathode

$$QE = P_O \cdot P_T \cdot P_E$$

2. Polarization Improvements

To overcome the 50% limitation, the degeneracy at the Γ point must be eliminated, by replacing the standard GaAs by new semiconductor materials, as shown in Fig. 3.

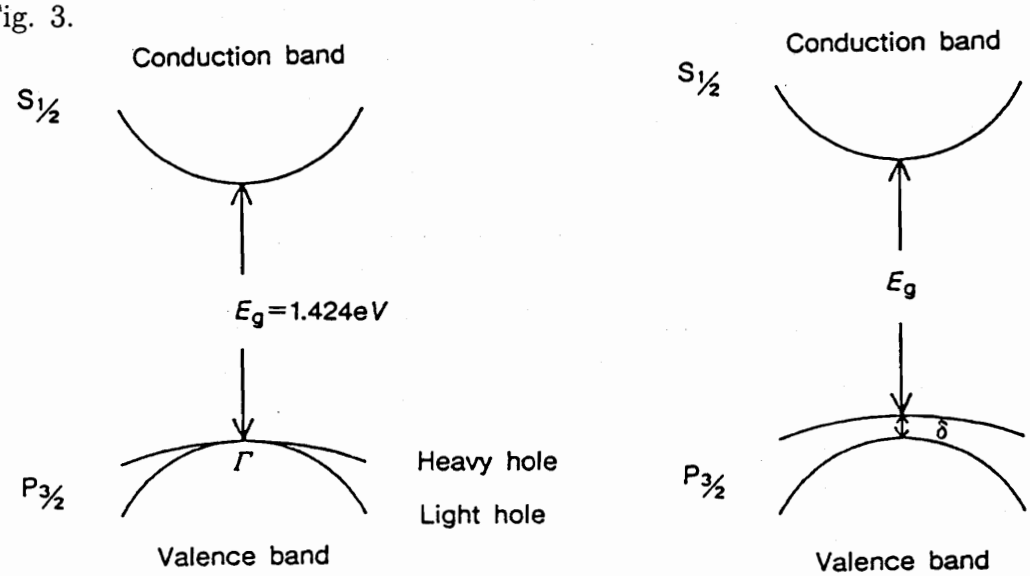

Fig. 3: Band Structures of Photocathodes made of GaAs and of New Materials

Since the GaAs-PES was invented in middle of 1970's, many attempts has been made to improve the relatively low degree of polarization of the GaAs source. Three candidates : ternary chalcopyrites, AlGaAs-GaAs superlattice, and strained GaAs have been examined. Several breakthroughs were independently achieved in 1991. Polarizations of 71% by AlGaAs-GaAs superlattice at KEK/Nagoya/NEC [6], 71%

by strained InGaAs at SLAC [7] and 86% by strained GaAs at Nagoya [8] were obtained.

2.1 Strained GaAs

The strained GaAs photocathode was made by growing a thin GaAs epilayer on a thick GaP_xAs_{1-x} buffer substrate by a MOCVD apparatus. Since the lattice constant of GaP_xAs_{1-x} is smaller than that of GaAs, biaxial in-plane compression is induced in the GaAs layer which results in tensile strain along the growth direction. Detailed understanding of the properties of a strained GaAs layer was achieved by experiments at Nagoya [9], SLAC [10], and St. Petersburg [3], and the following facts were established.

(1) The release of strain occurs partially in the GaAs layer, and more than $\sim$ 50% strain remains up to a thickness of a few tens of critical-thickness for coherent growth. This allows use of a (0.1$\sim$ 0.3) μm-thick GaAs layer.

(2) The ESP shows a clear dependence on the residual strain, and band splitting larger than 30 meV is required for an ESP higher than 80%.

The structure of the strained GaAs cathode and the strain dependence of the maximum ESP are shown in Fig. 4. [9] An ESP higher than 80% with a QE above 0.1% was achieved for the strained GaAs photocathode, and this type of photocathode was used successfully at SLC in the 1993 - 1995 run. [11]

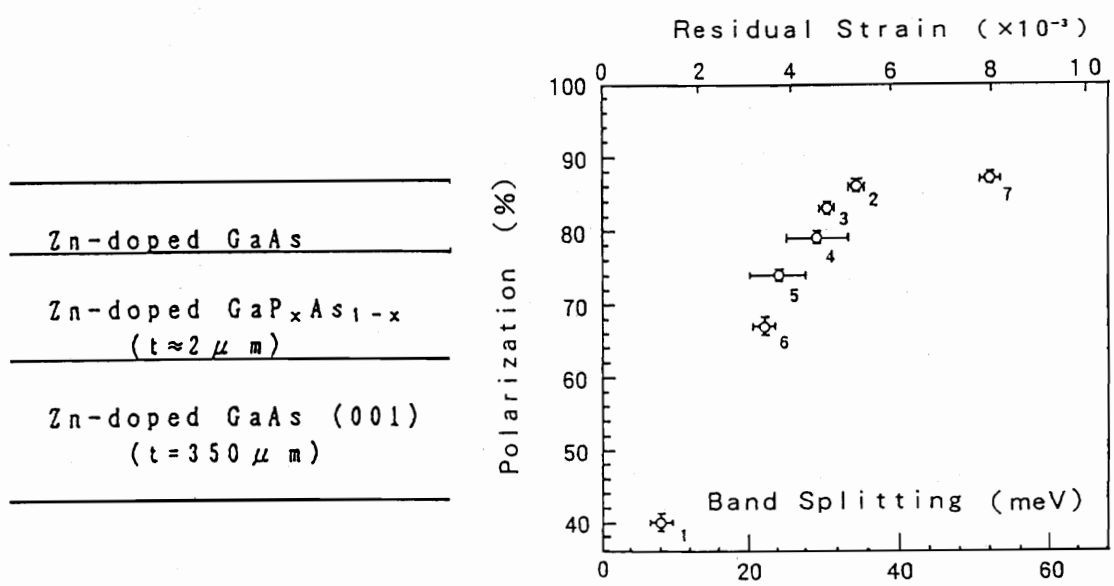

Fig. 4: Structure of Strained GaAs
and Strain-dependence of the Maximum Polarization

2.2 Strained Layer Superlattice

The superlattice (SL) is another interesting material, since it has more adjustable parameters than strained GaAs for designing a sample having both high ESP and high QE. After the first success of a GaAs-AlGaAs superlattice with an ESP of $\sim$ 70% and a QE of $\sim$ 0.01% [6], various samples were examined, and it became clear that this structure has a maximum ESP limit of $\sim$ 75%, probably due to band mixing between heavy and light holes.

To break this ESP limit, a new type of InGaAs-GaAs strained layer superlattice was studied at KEK/Nagoya/NEC. Both types of the band splitting due to strain and due to SL effects can be introduced into this band structure. An In fraction of 15% was chosen for the first sample. In this case, the InGaAs layers are strained, acting as potential wells for both electrons and heavy holes, while the GaAs layers are not strained, acting as potential wells for light holes. The energy splitting, defined as the difference between the hh and lh mini-bands, is estimated to be $\sim$ 30 meV. The maximum ESP of $\sim$ 83% with a QE of $\sim$ 0.02% was obtained at a laser wavelength of 911 nm, as shown in Fig. 5. [12] This success demonstrated the advantage of a strained layer superlattice, and trials for QE improvement are in progress.

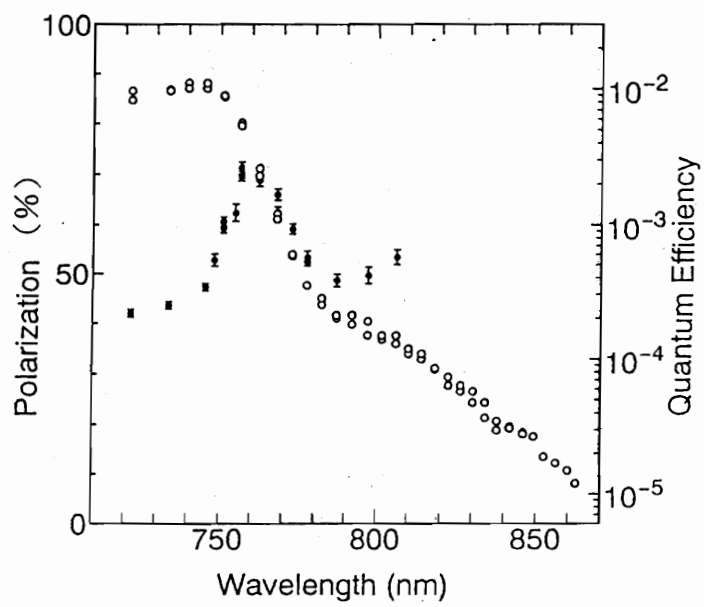

Fig. 5 : Quantum efficiency and Spin Polarization of Photoelectrons from Strained Layer Superlattice

3. Quantum Efficiency Improvements

In general, the photoemission process consists of three successive steps : optical absorption, electron transport, and escape across the surface. [5] Therefore the QE is the product of three probabilities related to these steps, and the up-grade of each probability can contribute to QE improvement. In view of this, the smaller QE (typically 0.1 %) of the new cathodes compared with that (typically 5 %) of normal

bulk-GaAs has an obvious origin in the first step. For high polarization cathodes, electrons are allowed to be excited only from the heavy hole band near the band-edge, which has the lowest state density. Moreover the thickness of the active strained layer is restricted to about 0.1 μm to prevent strain relaxation. This is true also for SL cathodes to avoid extensive depolarization inside the SL structure. [13]

3.1 Resonant Absorption Photocathode

To overcome QE limitations, "resonant absorption" was introduced into strained GaAs cathodes at Nagoya [14], as shown in Fig. 6. Incident laser lights are partially confined in a Fabry-Perot cavity which is formed by two parallel mirrors : a quarter-wave distributed Bragg reflector (DBR) and a surface boundary of GaAs and vacuum. The DBR was composed of 30 pairs of $Al_{0.1}Ga_{0.9}As$ and $Al_{0.6}Ga_{0.4}As$ layers and had a reflectivity higher than 90% within the laser bandwidth of ~50 nm. Significant QE enhancement is expected at the wavelength that satisfies the resonant condition : $2nL = m\lambda_R$ (m is an integer), where n, L are the refractive index and total length of the optical cavity.

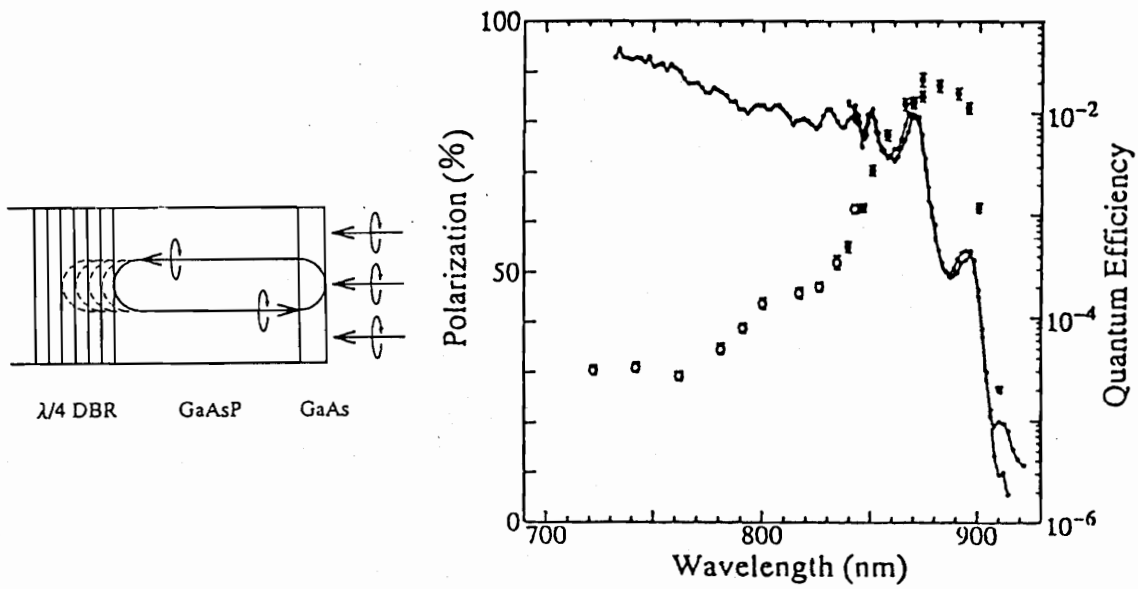

Fig. 6 : Quantum Efficiency and Polarization of Photoelectrons from Resonance-absorption-type Strained GaAs

In Fig. 6, the QE of the DBR cathode is indicated by the solid line, and the ESP by open and solid circles. A QE of ~1.0% is achieved at a wavelength of 860 nm which gives an ESP of ~85%.

One technical problem in fabricating the DBR cathode is the strict requirement for uniform thickness of the optical cavity made of many epi-layers. This was not

serious for the Nagoya experiment, where the laser spot diameter was less than 3 mmϕ, but it will be for a spot size as large as $\sim$ 20 mmϕ.

In principle, electrons of the same helicity are produced by reflected light as by incident light, because the photon circular polarization is reversed on reflection and so is the direction of electron emission, and this was demonstrated by the experiment at Nagoya. [14] Recently another strained $(Al_{0.3}Ga_{0.7})_{0.87}In_{0.13}As$ photocathode with a DBR was studied at Zürich; in this case depolarization was observed at the resonance absorption wavelength. [15] The authors explained this depolarization in terms of a small anisotropy of the in-plane lattice strain of their cathode sample.

3.2 Modulated Doping Superlattice

Another way to improve the QE of an AlGaAs/GaAs superlattice cathode was found at KEK/Nagoya/NEC. [16] Tests of various samples showed that both the ESP and the QE spectra of the laser wavelength are highly sensitive to the amount of Be-dopants. A typical result is shown in Fig. 7, where a shift in the polarization spectrum of the laser wavelength is clearly observed between two samples with different dopings.

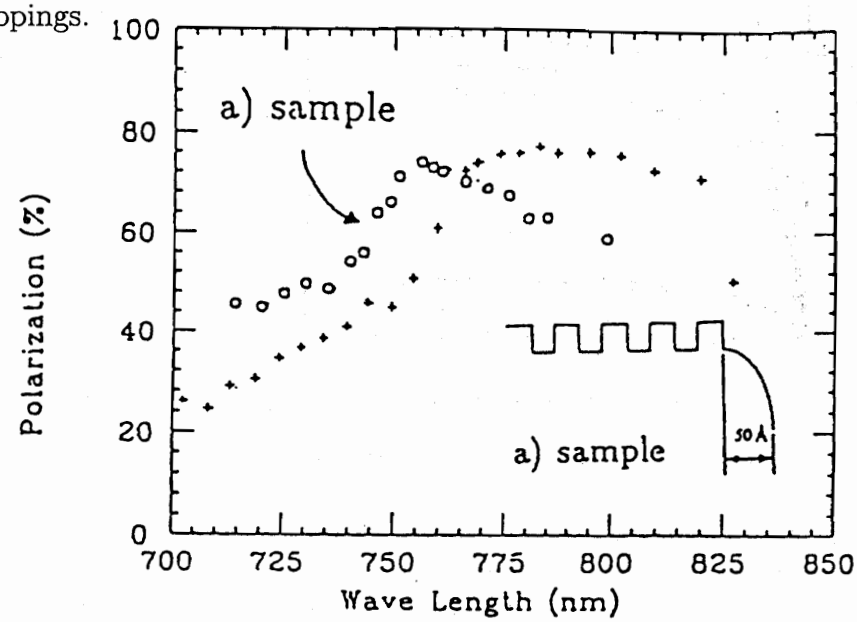

Fig. 7: A Shift of Polarization Spectrum due to Heavy Doping of GaAs Surface Layer

Both samples had the same Be-dopant density of $\sim 5 \times 10^{17}$/cc inside the superlattice structure, but one sample, labeled a), had a higher density of $\sim 4 \times 10^{19}$/cc only to the 50 Å-thick GaAs surface layer.

This wavelength shift is small, but it has a great effect on QE improvement, because the shorter wavelength photons can bring about a much higher QE than

the longer wavelength ones, especially at the threshold of band-gap excitation. A QE of $\sim$ 0.5% for an ESP of $\sim$ 70% at 757 nm was obtained for the a) sample by the Nagoya cathode-test-system, and a better QE value of $\sim$ 2.0% at 752 nm was achieved by the SLC gun-test-system. [17]

3.3 Charge Limit Effect

It is well known that the maximum peak-current extracted from a gun cathode is limited by the so-called space charge. An additional limitation on the total charge that can be extracted in a short period from GaAs NEA photocathodes was first observed at SLAC, and was named the charge limit (CL) phenomenon. [18] The observed charge saturation is shown in Fig. 8.

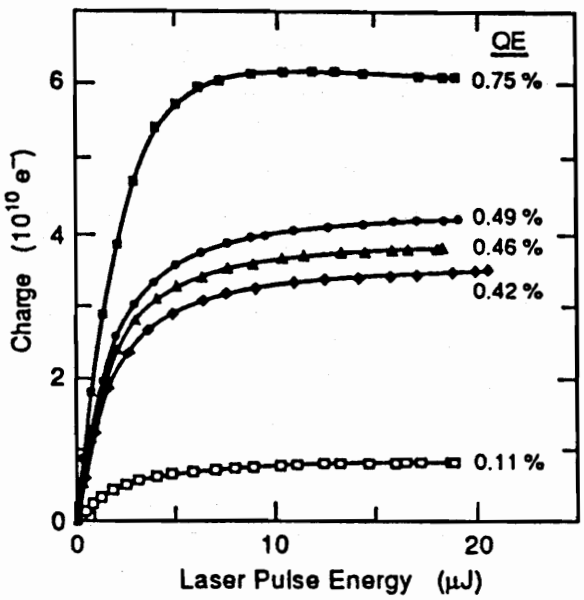

Fig. 8 :

Charge Saturation Curve Observed at SLAC for Bulk GaAs Cathode

These data were taken for five NEA states with different QE's, using a p-type bulk GaAs photocathode with Zn doping of 2×10^{19}/cc. The gun was operated at 120 kV, and the intensity of a laser pulse (2.8 ns width, 60 Hz) from a Ti:Sapphire laser was varied at the fixed wavelength of 765 nm.

The CL effect appears only during the production of a short electron pulse, and the explanation seems to be that some fractions of the electrons arriving at the NEA surface are trapped in the band bending region, when a large number of electrons are excited from the valence band to the conduction band under the intense illumination. These electrons induce additional photovoltage that may decrease the band bending of NEA and as a result suppress the emission of electrons arriving later at the surface. [19]

This interpretation suggests that the CL effect depends strongly on the NEA state, but is essentially independent of the thickness of the active layer. It means that new high polarization cathodes can supply the same intensity beam as can bulk

GaAs if the NEA surfaces are nearly equivalent [20], and this was demonstrated with strained GaAs [21] and superlattice [22] photocathodes.

An interesting result was obtained with a superlattice cathode with modulated doping, as shown in Fig. 9. A total charge of 2.3×10^{11} electrons in 2.5 ns was extracted with a bias voltage of 120 kV, which is a record performance by the SLC gun-test-system and corresponds to the charge that is limited by space-charge.

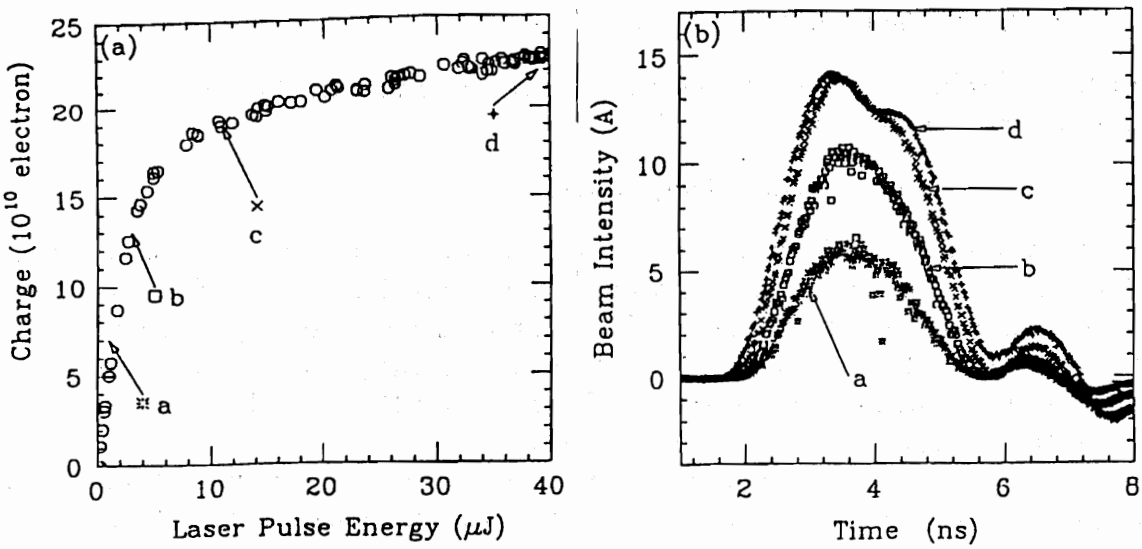

Fig. 9 : Charge Saturation Curve (a) and Related Beam Profiles (b) Observed at SLAC for AlGaAs/GaAs Superlattice

The CL effect is expected to become more significant for intense pulses with multi-bunch structure which will be employed at future e^+e^- linear colliders. Therefore it is both interesting and important to study the CL phenomenon under intense laser illumination with shorter pulse-widths and/or a greater number of bunches than that at the SLC. Future possibilities must be studied to develop a new kind of NEA-photocathode that has more resistant than GaAs to the CL effect.

Various efforts had been made to improve the QE, but they are not yet completed, and ample opportunities remain to search for new ideas and/or devices for fabricating a better photocathode.

4. Lifetime Improvements

The lifetime of the NEA state depends on various conditions of gun operation and ranges from a few hours to a few hundred hours before *in situ* re-cesiation and/or re-cleaning.

Two recommendations for gun design and construction have been made, to maintain long lifetime and high QE :

(1) Cathode contamination must be avoided by having the best vacuum attainable and by using a load-lock system.

(2) The pre-breakdown current (so-called dark current) between the high voltage electrodes must be suppressed, because it may cause vacuum degradation and ion bombardment of the NEA surface due to desorption on the anode. The desorption stimulated by the electron beam must also be suppressed by careful design of the beam transport line.

In the following, the basic physical processes concerning the lifetime problem are briefly surveyed and discussed.

4.1 NEA Surface Degradation

NEA degradation decreases the probability of electrons escaping from the conduction band to the vacuum. It is thought to be caused by two physical processes : (1) decrease of the band bending (BB) amplitude due to contamination by impurities trapped on the NEA surface, and (2) decrease of the probability of transmission into vacuum of conduction electrons arriving in the BB region, due to the increase of electron trapping states at the surface. [23]

Many papers have treated this subject; only a few are discussed here. NEA degradation was studied at Novosibirsk, by both photoreflectance (PR) and photoluminescence (PL) measurements, as shown in Fig. 10, where the BB amplitudes were estimated by analyzing the PR and PL spectra which were observed continuously during Cs-O_2 deposition cycles. [24]

A fine structure of energy spectrum of photoelectrons emitted from the NEA surface was first observed at Tohoku U. using a TOF spectrometer with high resolution of the order of a few meV. [25]

For improved resistance to the BB decrease, use of a wider band-gap semiconductor instead of GaAs appears promising. If we can assume that the work-function have a nearly common value for the GaAs-type semiconductors, a larger NEA value should be attained by wider band-gap material, which offers higher QE and better NEA stability. In fact, a strained InGaAsP layer grown on GaAs substrate had a lifetime one order better than GaAs was observed at Novosibirsk [26], although an ESP much higher than 60% has not yet been reported. There is room to improve ESP performance by other new wide band-gap materials; one candidate might be a semiconductor with chalcopyrite structure.

Another study to identify the poison elements that degrade the NEA state was made, for example at Mainz, where the amounts of cesium, carbon and oxygen on a NEA GaAsP surface were measured by x-ray photoelectron spectroscopy (XPS) during the activation cycles. [27] They suggested that Cs atoms are tightly bound to the GaAs or GaAsP surface, and that NEA fatigue is not due to thermal deposition of Cs atoms at room temperature.

The bondings of O_2, CO_2, and CO on a NEA-GaAs surface was also studied at Tohoku U. using thermal desorption spectroscopy (TDS) [27], and the influence of exposure to CO, CO_2 and H_2O on the stability of the NEA surface was also studied at Shizuoka U. [27]

The poison elements are not yet identified completely, and it seems important to continue such a fundamental study by improving the sensitivity of the apparatus.

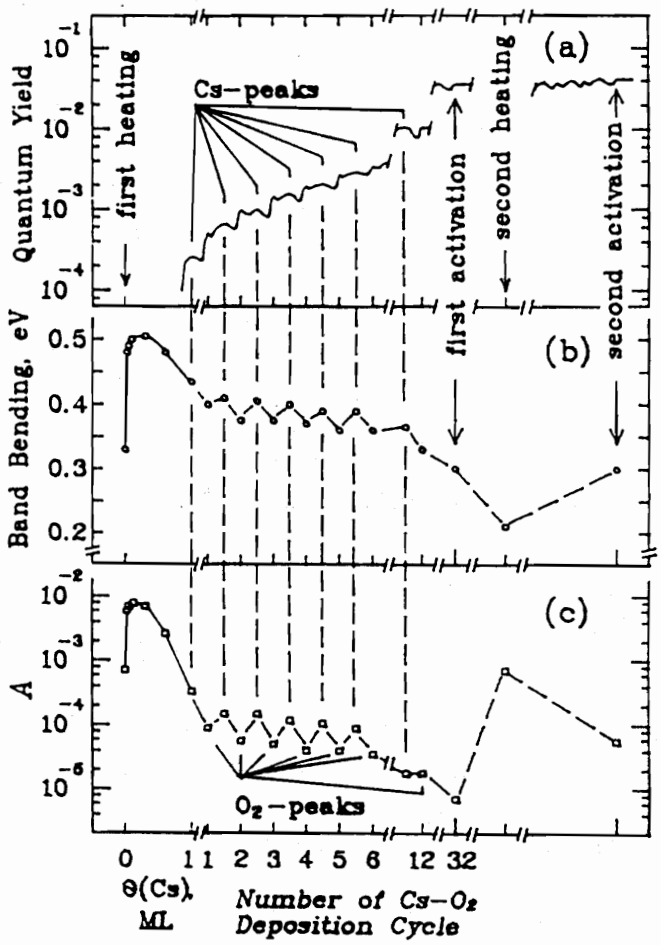

Fig. 10: Evolution of Quantum Yield (a), Band Bending (b), Photoreflectance (c), at Multiple Cs-O_2 Deposition Cycles

4.2 Dark Current

Because activated NEA cathodes are extremely sensitive to contamination, the contaminants caused by the high voltage (HV) pre-breakdown current (so-called dark current) must be minimized to maintain good QE and long lifetime. The dark currents at a level as low as 100 nA were reported to degrade the lifetime and irreversibly reduce the QE at SLAC [11, 28] and at Mainz [29]. Fig. 11 shows the correlation between cathode lifetime and dark currents observed at Mainz. [29]

Dark currents are caused by field emissions from metal surfaces, which occur when the electric fields are high enough to lower the metal surface potential barrier sufficiently for electrons to tunnel out. [30] The local electric field can be enhanced by several orders of magnitude (microscopic field enhancement factor, β) by the presence of microscopic irregularities (pittings or scratches) or of non-metallic impurities or dust. [31]

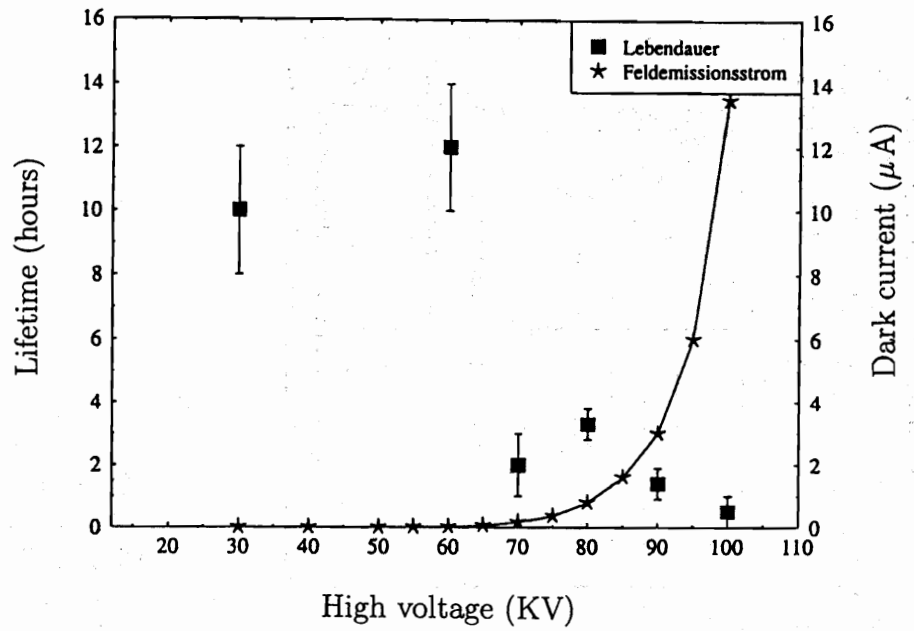

Fig. 11 : NEA Lifetime and Dark Currents as a Function of Applied High Voltage

Therefore, many careful treatments are required during various stages of construction and operation of the PES gun to realize and maintain a low level of dark current. The following recommendations have been made by various groups.

(1) The electrodes must be designed to reduce the maximum field strength, using the simulation code.

(2) A material with low impurity content and low porosity must be chosen for electrodes. [11, 29, 32]

(3) The surfaces of the electrodes must be carefully polished, e.g. with diamond paste or Al_2O_3 powder to 0.5μm finish [11, 29, 32]

(4) Rinsing with ultra-pure-water just before assembly is effective in providing a clean surface. [32]

(5) Assembly of the gun must be done in a clean room.

(6) High voltage processing techniques are effective in reducing the dark current. [11]

(7) The load-lock system is essential for optimum performance. Over-cesiation helps to extend the lifetime, and it can be done by using the load-lock without the risk of HV breakdown. [11]

Excellent work has been done at SLAC, and a dark current of 10 to 50 nA was maintained by the SLC gun operated at 120 kV with a total pressure of $\sim 2 \times 10^{-11}$ torr. [11] The best lifetime, ~1,200 hours, was achieved for a strained GaAs cathode with a dark current of only 10 nA. Typical behavior of QE variation in the 1993 SLC run is shown in Fig. 12, where the QE was monitored at a laser wavelength of 833 nm and the cathode was excited at 865 nm. There were 29 re-cesiations during this period of ~140 days.

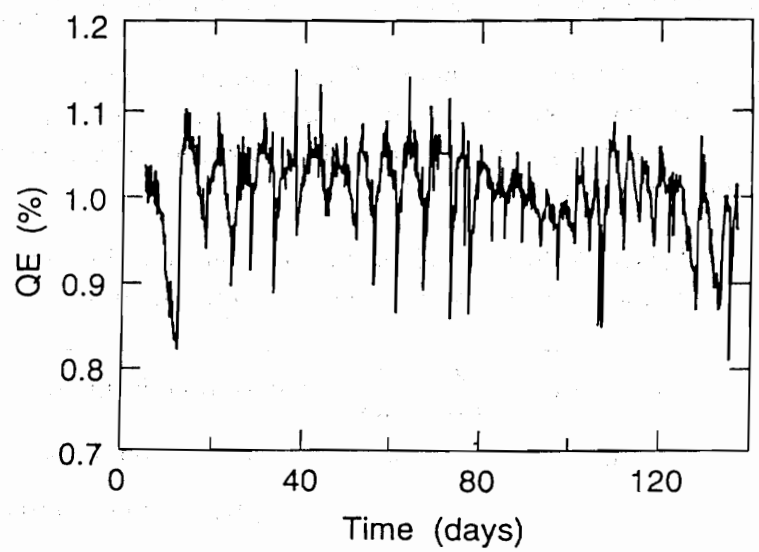

Fig. 12: Monitored Quantum Efficiency during the 1993 SLC Run

5. Summary

Typical values of ESP and QE obtained with various types of photocathodes are given in Table 1. Polarized electrons from bulk GaAs, thin GaAs and thin GaAsP cathodes had already been used in experiments at SLAC, MIT/Bates and Mainz, with ESP's of (30~40)%. Strained GaAs became the first high polarization cathode with ESP≥80% used in SLC experiments from 1993. This cathode has already made an essential contributions to increasing accuracy in determining the Weinberg-Salam angle.

Research has continued in developing new cathodes with better performance than strained GaAs. The possibility of a QE higher than 1% with an ESP≥70% has already been demonstrated by both "strained GaAs with DBR" and "modulated doping AlGaAs/GaAs superlattice" cathodes. An ESP higher than 80% was also achieved by a "InGaAs/GaAs strained layer superlattice" cathode.

In the near future, more electron machines will be able to accelerate the polarized e^- beam with excellent performance not only in ESP and QE but also in lifetime and beam emittance. With respect to beam emittance, the polarized RF gun seems to be the most attractive; it offers possibility of eliminating the subharmonic buncher at low energy and reducing the role of the damping ring. [33]

However, several serious problems are expected. One is the vacuum contamination induced by dark current in an RF cavity, which destroys the NEA state quickly and lowers the QE. Another is the CL effect, which limits the peak current from the photocathode. In addition, the speed of the time response of the NEA cathode to the ultra-short ($\leq$ sub-nanosec) laser pulse must be studied, since it is expected to be much slower than that of the metal cathode. [5, 34] The experimental studies on these problems have already being started by several groups with international collaborations.

As a final comment, I think, the fields of semiconductor photoemission sources is still largely open to development of wider applications for polarized e^- beam in various areas of physics in the near future. For example, the polarized RF gun provides an attractive challenge.

Table 1 : Typical Values of Polarization and Quantum Efficiency Available with Various Types of Photocathodes

Photocathode	Thickness	Quantum Efficiency	Polarization	Institute
Bulk GaAs	~1.0 μm	~5 %	~30 %	ETH (1976)
GaAsP		~1 %	~40 %	Mainz (1982)
Thin GaAs	~0.3 μm	~0.3 %	~45 %	SLAC (1988)
Strained InGaAs	~0.1 μm	~0.01 %	~70 %	SLAC (1991)
Strained GaAs	~0.1 μm	~0.1 %	~85 %	Nagoya (1991)
Strained GaAs with DBR	~0.1 μm	~1.3 %	~85 %	Nagoya (1993)
Strained InGaAsP	~0.1 μm	~0.05 %	~60 %	Novosibirsk (1993)
Superlattice	~0.1 μm	~0.1 %	~75 %	KEK / Nagoya (1991)
Modulated Doping Superlattice	~0.1 μm	~1 %	~70 %	KEK / Nagoya (1992)
Strained-Layer Superlattice	~0.1 μm	~0.02 %	~83 %	KEK / Nagoya (1994)

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