Photocathode Development for Highly Polarized Electron Sources

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Abstract

For long years, the available spin polarization of electron beam supplied by normal GaAs photocathode had been limited below 50%. The breakthrough was recently achieved by the developments of new material photocathodes of strained GaAs, strained InGaAs and AlGaAs-GaAs superlattice.

The performance of more than 80% polarization for 0.1% quantum efficiency was already demonstrated by the strained GaAs photocathode with a test apparatus. The properties of such photocathodes are described in this paper. The remaining problems expected to meet in application to the high energy accelerators are also discussed referring the recent data reported by SLC polarization group.

1. Introduction

Recently polarized electron is considered as an important tool in particle physics and many accelerators have prepared it. For examples, SLC just runs at Z_0 pole with polarized beam. SLAC, Mainz, CEBAF, Bonn and others have plans to measure the structure functions of proton and neutron, the electric form-factor of neutron, the DHG sumrule and so on by using the polarized electrons. It is also expected that polarized e^- beam makes an essential role in the future e^+e^- linear collider experiments.

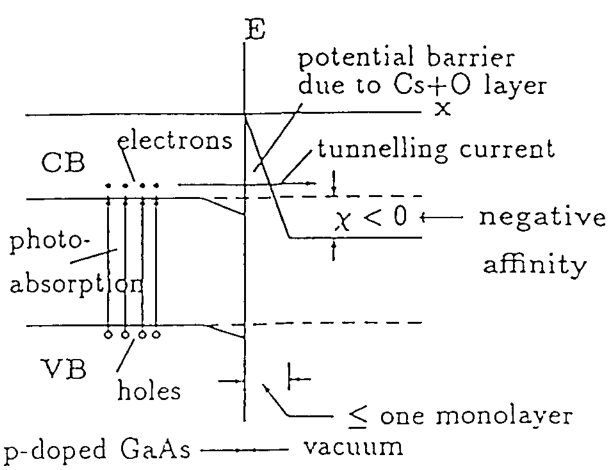

Figure 1. Principle of polarized electron source with GaAs photocathode [2].

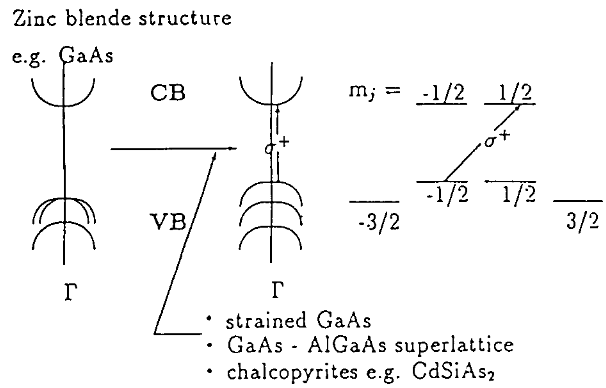

Figure 2. The band structures of GaAs and new photocathodes [2].

In answer to such urgent needs, the polarized electron source (PES) technology has also been developed powerfully, which seems to promise the dramatic improvements over earlier source performances [1].

Historically, various types of gas ionization PES were developed, however, only the GaAs type PES has been demonstrated to meet the source requirements from high energy physics experiments. Although the principle of GaAs-PES was described in many places [2], a brief review is given here to provide a basis of understandings for the physics and technology behind the recent improvements of the source performances.

The GaAs-PES is based on a combination of two fundamental technologies ; laser optical pumping and negative electron affinity (NEA) surface of semiconductor as shown in fig.1. The former is responsible to the electron spin polarization (ESP) mechanism that the conduction band electrons excited from Γ point (the top of the valence band) are polarized due to the selection rule for the circular polarized photon absorption. The maximum degree of ESP is determined by the properties of the fine splitting of the band structure. For GaAs, it is 50% due to the degeneracy between heavy-hole(hh) and light-hole(lh) bands at Γ point as shown in fig.2. Recent breakthrough against this 50% limitation is explained in the next section.

The NEA technique is responsible to the electron emission from conduction band to vacuum. The treatment of heavily p-doped GaAs surface by monolayer coverages of alkali metals and oxidants ($Cs + O_2$ or $Cs + NF_3$ is usually used) lowering the working function to the point where the electron can diffuse into vacuum freely as shown in fig.1. The NEA surface has a great advantage to extract the high current from the cathode with an excellent quantum efficiency (QE) of (1~ 10)%. On the other hand, it also brings non-trivial difficulties for the source operation, especially at high energy accelerator. For achieving and maintaining the good QE, the NEA surface must be free of adsorbed residual gases (CO, CO_2 and others) at the sub-monolayer level, which requires the very careful treatment of photocathode in the ultra high vacuum of ($10^{-10} \sim 10^{-11}$) torr range. Obviously the lifetime of photocathode is also governed by the NEA state, which depends mainly on the vacuum condition of each apparatus and ranges from a few hours to a few hundred hours before *in situ* re-cleaning and/or re-cesiation [1].

We discuss again on the problems of operational source in the last section, in relation to the feasibility consideration of new photocathodes.

2. Photocathode Development

As stated in the introduction, the theoretically - attainable ESP by normal GaAs photocathode is limited below 50%. For overcoming this limitation, the degeneracy at Γ point must be removed as shown in fig. 2, replacing GaAs by the new semiconductors.

In the spring of 1991, polarizations of 71% by AlGaAs-GaAs superlattice [3], 71% by strained InGaAs [4] and 86% by strained GaAs [5] photocathodes were observed at Nagoya-KEK, at SLAC and at Nagoya, respectively. After those breakthroughs, more systematic studies to understand the detailed properties of new cathodes have been made by several groups including ETH-Zürich and Illinois/CEBAF.

At present, the strained GaAs photocathode is considered most promising due to its higher ESP and also better QE(quantum efficiency) than others. By strained GaAs photocathode, the QE more than 0.1% was already

Zn-doped GaAs
Zn-doped GaP_xAs_{1-x} ($t \approx 2\,\mu m$)
Zn-doped GaAs (001) ($t = 350\,\mu m$)

Table 1. Structure of samples of strained GaAs photocathode [5].

The phosphorus fraction (x) and the thickness (t) of GaAs epilayer was chosen as x=0.17 and t=850Å.

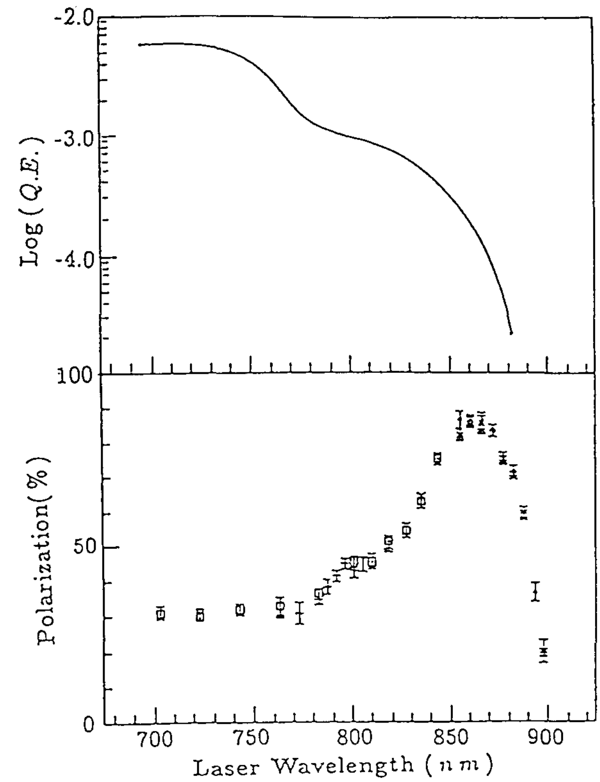

Figure 3. The quantum efficiency and polarization as a function of laser wavelength for strained GaAs photocathode. [5]

achieved with the polarization higher than 80% at Nagoya [6] and at SLAC [7].

2.1 First strained GaAs photocathode

The first successful strained GaAs photocathode was made by Nagoya group, growing a GaAs epilayer on a lattice mismatched GaP_xAs_{1-x} buffer substrate by a MOCVD apparatus. The structure of prepared sample was rather simple as shown in Table 1, where the phosphorus fraction and the GaAs epilayer thickness were chosen as $x = 0.17$ and $t = 850Å$. Since the lattice constant of GaP_xAs_{1-x} is smaller than that of GaAs, biaxial in-plane compression is induced and it results in the tensile strain to GaAs layer along the growth direction. The ESP and the QE observed for this strained GaAs photocathode are plotted in fig. 3, as a function of laser wavelength. The QE increases in two steps. The first(second) rise begins at the threshold energy of interband excitation from the GaAs(GaP_xAs_{1-x}) layer. The clear ESP peak of 86% at $\lambda \approx 860nm$ is the evidence of the single excitation from the upper hh-band of the strained GaAs. Due to additional contributions from the lower lh-band, the ESP decreases to the shoulder(~ 46%) at $\lambda \approx 800nm$. The further drops below $\lambda \approx 780nm$ is caused by the electrons excited from valence band of the GaP_xAs_{1-x} buffer layer. By this cathode, one of the problem in this field seemed to be settled, in principle.

However, there still remained another problem, the relatively poor QE for the new cathodes. For example, the QE was $\sim 0.02\%$ for the above sample at $\lambda \approx 860nm$, while the QE more than a few % is possible for the bulk GaAs cathode. The QE limitation comes mainly from the fact that only the single excitation from hh(lh) band is allowed for obtaining the highest ESP. The electrons are excited from the very low density of state near the band edge, resulting in low photocurrent density. This situation might be slightly improved by enlarging the energy splitting between hh and lh bands, making the highly strained GaAs layer. On the other hand, it is not so easy to make a thick epilayer with large strain, since the dislocations cause the relaxation of the strain. In addition, for the thick layer photocathode, the depolarization inside GaAs becomes so significant that the available thickness of GaAs epilayer seems to be restricted to be $(0.1 \sim 0.3)\,\mu m$ to get the higher ESP than 80%.

2.2 Strain dependence of polarization

For more detailed treatment of the strained GaAs cathode, the following experimental data seemed to be indispensable, [I] Correlation between residual strain, lattice mismatch and GaAs epilayer thickness and [II] Dependence of the polarization on the residual strain in GaAs epilayer. In order to take such data, Nagoya and SLAC groups made samples with different (x, t) parameters. The X ray diffraction analyses were done to determine the strained lattice constant for each sample.
Concerning [I], a two dimensional plot of $\varepsilon_R/\varepsilon$ and t/t_c using the data of Nagoya and SLAC samples is shown in fig. 4 [6],[7]. In spite that each sample had a different combination of (x, t), there seems to be the correlation between

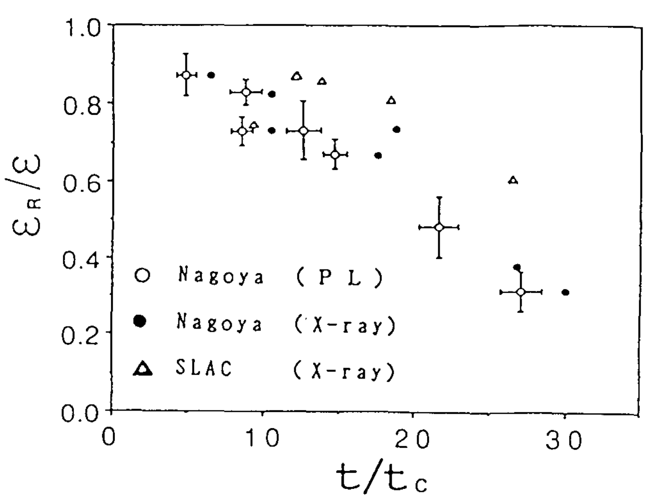

Figure 4. Two dimensional plot of $\varepsilon_R/\varepsilon$ and t/t_c for strained GaAs photocathode [6],[7].
The ε and the ε_R are the lattice mismatch and the residual strain. The t_c is the critical thickness for coherent growth, evaluated by Matthews' formula.

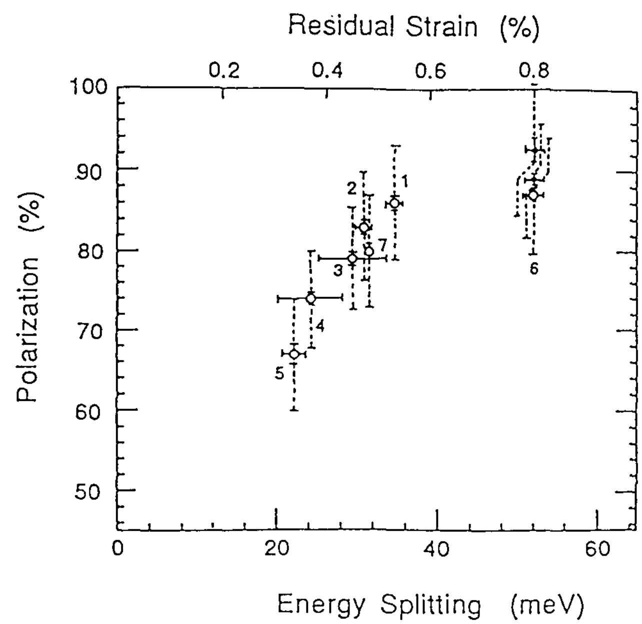

Figure 5. Strain dependence of electron spin polarization for strained GaAs photocathode [6].
Statistical (solid line) and systematic (dashed line) errors for the ESP determination are indicated.

$\varepsilon_R/\varepsilon$ and t/t_c and this curve is useful for designing the strained GaAs photocathode. It is also shown from fig. 4 that the release of strain occurs partially in the epilayer, remaining more than $\sim 50\%$ strain up to the thickness of a few tens of t_c. Concerning [II], the maximum ESP attained by Nagoya samples was plotted in fig. 5, as a function of its residual strain [6]. There, the upper axis of abscissas indicates the residual strain and lower one does the corresponding band splitting. Such a strain dependence was firstly observed by measuring the ESP of extracted electrons. As shown in fig. 5, the ESP has a clear dependence on the strain, especially for the region of small band splitting. For region of larger band splitting, the increase of ESP seems to be suppressed at the level of $\sim 90\%$.

On the contrary of such a data, the theory predicts as $P_{hh} = -100\%$ ($P_{lh} = 100\%$) for photoelectrons exited from the top of hh (lh) band to conduction band. At present, the discrepancy between theory and experiment is not yet clearly understood. However, some speculations can be made [6]. Concerning the gap between 100% and the observed $\sim 90\%$, the effect of band-mixing between hh and lh bands for the electrons with momentum $k \neq 0$ must be considered. The effect of band tails for the band-edge absorption must also be taken into account, which would smear out the small band splitting and cause the decrease of ESP. The magnitude of the band fluctuation would depend on the temperature of cathode, the p-doping density, the number of defects and so on. Thus, the ESP data taken from the photocathode with different parameters or those taken under different conditions would be helpful for further quantitative discussions.

2.3 Superlattice

Due to the quantum size effect, the degeneracy at Γ point is also lifted in the superlattice (SL). KEK-Nagoya-NEC group has developed this type of photocathode for recent a few years. As results, the maximum ESP of 75% with QE ≈ 0.01% was obtained by the sample which consists of 20 wells with a total thickness of $0.1 \mu m$ and a p-doping density of $\sim 5 \times 10^{17}/cm^3$ [8]. Recently an interesting sample was examined by changing the fine structure of SL surface, which gave the standard ESP of 71%, but much better QE of ~ 0.2%. Further parameters optimization has been continued to get better performances.

3. Application of strained cathodes

As applications of polarized e^- beam, there considered three different cases which depend on the accelerator and experiments, such as, 1) low and medium intensity CW beam with polarized target, 2) intense CW beams for high Q^2 or parity violation experiments and 3) high peak current beams for linear colliders [1].

In table 2, the typical values of ESP and QE obtained by four kinds of photocathodes are summarized. For evaluation of advantages of new cathode, we discuss about the figure of merits of the sources by $P^2 I/I_0$, where P equals to ESP, I and I_0 denote the available intensity and the maximum intensity accepted by an injection linac or by experimental conditions, respectively.

Cathode	ESP (%)	QE (%)	Ref.
Bulk GaAs	~ 40	5 ~ 10	[1]
Thin GaAs	~ 47	~ 2	[9]
Strained GaAs	~ 80	~ 0.1	[6],[7]
Superlattice	~ 70	~ 0.2	[8]

Table 2 : Photocathodes performances

For application of case 1), the use of new strained cathode is the best choice without problems, since I≈ I_0 seems easily achieved. In the case of 2) and 3), it seems not so straightforward at present and needs some experimental studies, since the available current(I) might be limited by the combination of low QE of strained cathode and the limit imposed on the laser power to avoid "laser burning" phenomena.

For application of strained cathode to the linear colliders, the first successful PES operation at SLC seems to contain much informations, although the bulk GaAs has been used there. The gun has produced 120 keV polarized electrons with intensity of 6×10^{10} e⁻ (5 A peak current) in a 2 ns bunch, which is as same as normal e^- beam. Other performances are the initial QE of (5~ 10)%, lifetime of a few days and the average ESP of ~ 28 %, where the cathode temperature has been kept at $\sim 0°C$ [10]. The typical history of QE during the run is shown in fig. 6. Such performances of SLC gun seems to be perfect, except the low ESP due to the use of bulk GaAs cathode. Obviously as a next step, it is urgently required to replace it by the new cathodes with much higher ESP.

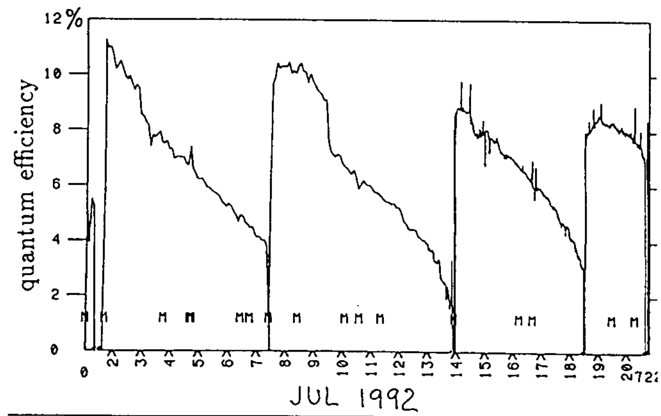

Figure 6. A typical history of quantum efficiency of SLC source during the run operation [10].

To produce the same intensity as bulk GaAs, the laser power must be increased by a factor of ~ 100 for strained cathode. A deterioration in QE of bulk GaAs cathode was reported to occur when average laser power exceeded a level between 5 and 20 watts/cm² [1]. This limit for strained cathode must be confirmed by experiment, hopefully in very near future. Of course the development of high power laser tuned to the wavelength around $\lambda \approx 860\,nm$ is also important for strained GaAs cathode.

Recently another interesting phenomena called "charge limitation" was also observed at SLAC. The data shows that the maximum charge extracted from a bulk GaAs cathode near band gap threshold in a short pulse can be less than the space charge limit [11]. This behavior of saturation is significant for the cathode with low QE and the charge limit seems to be proportional to QE, as shown in fig.7. Although the reason is not yet fully understood, SLAC people try to explain such a behavior using the concept of the solid state plasma produced inside GaAs[12]. The key feature seems to be the bad NEA surface which causes the increase of plasma density in solid, resulting in the "charge limitation", as the plasma state prevents the conduction electrons to escape into vacuum.

It must be remarked that this phenomena is expected to occur also for strained GaAs cathode in the case of bad NEA surface, but the "charge limit" may be as same as for bulk GaAs in spite of its intrinsic low QE. However, this

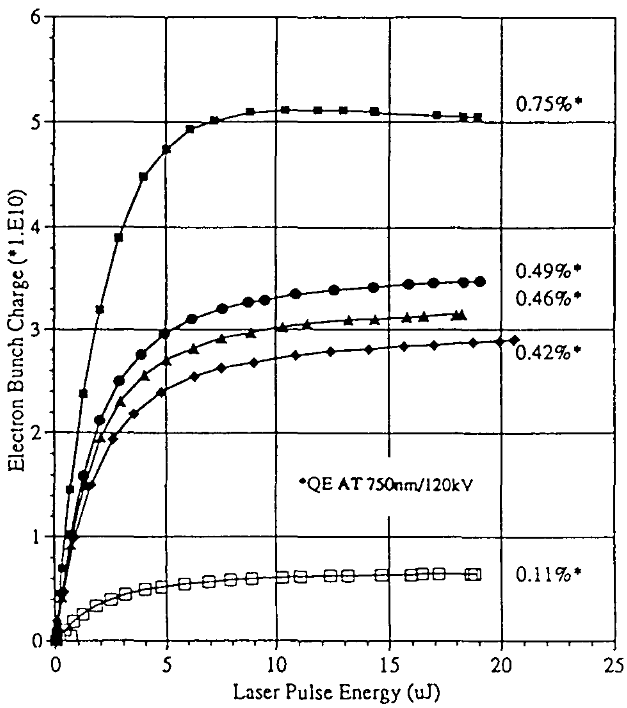

Figure 7. The data of "charge limitation" [11]. This data was taken for bulk GaAs cathode pumped by Ti:Sapphire laser with $\lambda = 765\,nm$.

prediction must be also confirmed by experiment, hopefully in very near future.

In conclusion, the photocathode development for highly polarized electron sources made great advances over the last few years supported by the recent crystal-growing technology. By the strained GaAs cathode, the ESP more than 80% with the QE $\approx$ 0.1% is routinely obtained by the test apparatus. For applications of this cathode to accelerators, there seems no fatal limitations at present, although both of laser power limitation and "charge limitation" must be checked by the experiments.

References

[1] L. S. Cardman, NPL-91-014 published in *Proc. of the ESP Conf. on Hadronic Structure and Electroweak Interactions, Amsterdam, 1991*

[2] E. Reichert, in *Proc. of the 9th Int. Sympo. on High Energy Spin Physics, Bonn, 1990* Vol. 1,303

[3] T. Omori, Y. Kurihara, T. Nakanishi, H. Aoyagi, T. Baba, T. Furuya, K. Itoga, M. Mizuta, S. Nakamura, Y. Takeuchi, M. Tsubata and M. Yoshioka, Phys. Rev. Lett. 67 (1991) 3294-97

[4] T. Maruyama, E. L. Garwin, R. Prepost, G. H. Zapalac, J. S. Smith and J. D. Walker, Phys. Rev. Lett. 66 (1991) 2376.

[5] T. Nakanishi, H. Aoyagi, H. Horinaka, Y. Kamiya, T. Kato, S. Nakamura, T. Saka and M. Tsubata, Phys. Lett. A158 (1991) 345-349

[6] H. Aoyagi, H. Horinaka, Y. Kamiya, T. Kosugoh, T. Kato, S. Nakamura, T. Nakanishi, S. Okumi, T. Saka, M. Tawada and M. Tsubata, Phys. Lett. A167 (1992), 415-420

[7] T. Maruyama, E. L. Garwin, R. Prepost and G. H. Zapalac, SLAC-PUB-5731/WISC-EX-92-322

[8] Y. Kurihara, T. Omori, T. Nakanishi, H. Aoyagi, T. Baba, T. Furuya, K. Itoga, M. Mizuta, S. Nakamura, Y. Takeuchi, M. Tsubata and M. Yoshioka, Nucl. Instrum. Methods A313(1992)393-397

[9] T. Maruyama *et al.*, Appl. Phys. Lett. 55(1989)1686

[10] J. E. Clendenin, Private Comunication

[11] M. Woods et al. SLAC - PUB - 5894 (1992) to be submitted for Publication

[12] M. Zolotorev , " Nonlinear Effects in Photocathode ", to be submitted for publication