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Abstract

Our collaboration group have continued the research to develop the high performance photocathode and the guns to produce the highly polarized electron beam for high energy accelerator physics. In this report, the experimental results obtained from the photocathodes with superlattice structures, such as, AlGaAs-GaAs, InGaAs-GaAs and InGaAs-AlGaAs are described.

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Abstract. Our collaboration group have continued the research to develop the high performance photocathode and the guns to produce the highly polarized electron beam for high energy accelerator physics. In this report, the experimental results obtained from the photocathodes with superlattice structures, such as, AlGaAs-GaAs, InGaAs-GaAs and InGaAs-AlGaAs are described.

1. Introduction

Nowadays, polarized electron beam is most conventionally produced by using photoemission from the GaAs-type-semiconductor source. This polarized electron source (PES) is based on a combination of two fundamental technologies : laser optical pumping and a semiconductor surface with negative electron affinity (NEA). Followings are considered as the most important performances for PES-photocathodes used at High Energy electron accelerators (1).

1) electron spin polarization (ESP),
2) quantum efficiency (QE),
3) high peak current or high average current of extracted beam
4) cathode life time.

The maximum degree of electron spin polarization (ESP) seems to be governed mainly by two physical mechanisms. One is related to the initial polarization (Pi) of excited electrons in the conduction band, and Pi will be determined by the band-mixing of heavy-hole (hh) and light-hole (lh) bands at the valence band maximum. The other is related to spin relaxation process which will take place both at an inside and a surface of the semiconductor. The depolarization will become significant, if the spin relaxation time (τ_s) is much shorter than the average time (τ_{esc}) required for electrons to escape into vacuum. The spin relaxation time can be measured by photoluminescence method, and is discussed later in section **6**.

To overcome the 50% ESP limitation of bulk-GaAs, the fine energy splitting (δ_s) must be given between hh- and lh-bands, and several different types of photocathodes have been developed by our collaboration. They are categorized into two groups. One contains the thin layers of strained GaAs (2), strained GaAsP, and strained GaAs with DBR (distributed Bragg reflector) (3). The other contains unstrained superlattice of AlGaAs-GaAs (4), strained layer superlattice of InGaAs-GaAs (5) and InGaAs-AlGaAs (6). Those superlattice have been fabricated by NEC Corporation using the molecular-beam epitaxy (MBE) method. AlGaAs-GaAs and InGaAs-GaAs are described in sections **2** and **3**, and new results of InGaAs-AlGaAs are given in section **4**.

The NEA surface plays an indispensable role in electron emission into vacuum, and the quantum efficiency (QE) is mainly governed by the properties of this NEA surface. The QE decay rate (defined as a cathode life time) is the most important performance for stable operation and easy maintenance of the source. The wider band-gap semiconductor cathode is considered as more favorable both for the higher QE, and the longer life time, because it gives the larger NEA. This problem is discussed again in section **4**.

The maximum extracted current is determined by space charge limit for a thermionic gun cathode, while there is another limit called "surface charge limit" (SCL) for the NEA cathode of GaAs-PES, which was first observed at SLAC (7), (8). This suppression for emission of conduction-band electrons is considered as caused by electron trapping in the band bending region (BBR) of NEA surface. Therefore, SCL depends on conditions of the NEA state at BBR, as well as, a magnitude of extraction-field-gradient at the surface. The AlGaAs-GaAs superlattice with a highly p-doped NEA surface showed the higher resistance against SCL than that of strained GaAs (9), (10). New experimental data on this SLC effect is given in section **5**.

2. AlGaAs-GaAs Superlattice

It was demonstrated in 1991 that electrons with high polarization of ~70% can be extracted from the AlGaAs-GaAs superlattice (4). Since then, various samples of AlGaAs-GaAs superlattice were made and tested, and it turned out that both of ESP and QE are quite sensitive to the amount of Be-dopants. Namely, to avoid the spin depolarization, the medium Be-density ($\sim 5 \times 10^{17}/cc$) inside the superlattice is preferable, while the high Be-density such as $\sim 4 \times 10^{19}/cc$ at the BBR (5 nm thickness) is so effective to increase the QE.

By this modulation doping technique, the QE becomes more than 0.5%, one order of magnitude higher than that of the previous uniformly-doped one, as shown in Fig. 1(a). High QE of this cathode (named as SL#7) was also confirmed at the tests at SLAC, Mainz and Bonn (12). As shown in Fig. 1(b), the thickness of GaAs (AlGaAs) layer is 1.98 nm (3.11 nm), and the total thickness of active layer was chosen to be about 0.1μm (20 pairs) to reduce spin

depolarization during the emission process. The calculation of energy band structure by Kronig-Penny-Bastard (11) model shows that an energy splitting (δ_s) defined as the difference between both of the upper levels of hh- and lh-mini-bands is 23 meV.

Figure 1(a)

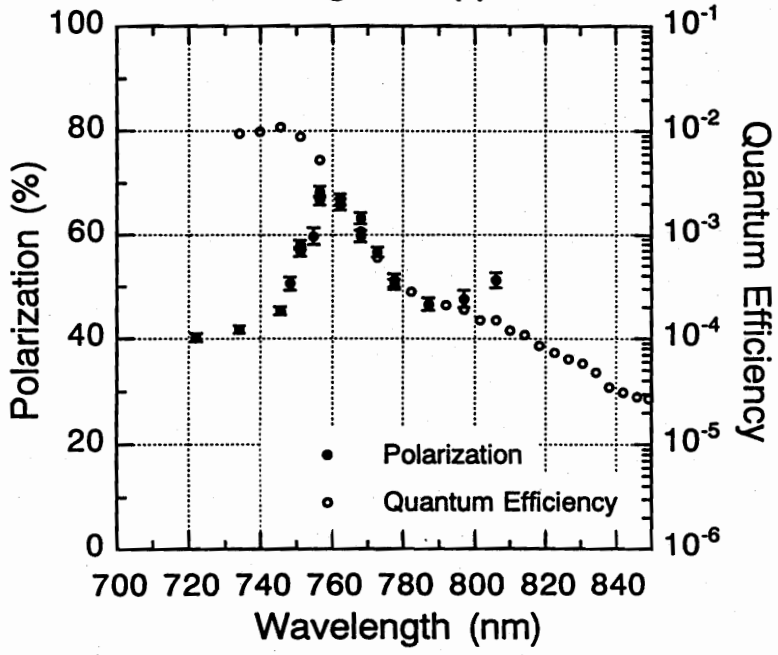
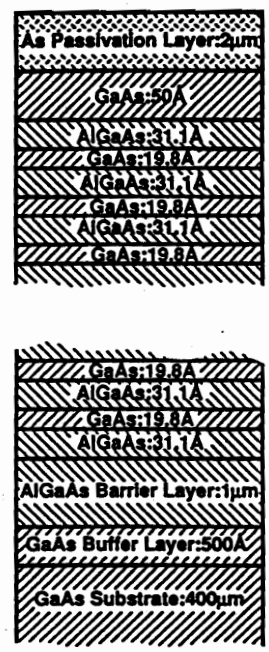


Figure 1(b)



The polarization dependence on the thickness of AlGaAs-GaAs superlattice samples was measured and it turned out that the maximum ESP is limited to be 75% even if the so thin layer of superlattice is used (13). It suggests that the spin depolarization inside the superlattice whose thickness less than $0.1\mu m$ is not so serious, while the initial polarization (the ESP at excitation) itself is insufficient. It is probably due to the band mixing between hh- and lh-bands in the $k\perp$ (wave vector perpendicular to the excitation light)$\neq 0$ states, which is characteristic feature for the superlattice structure.

3. InGaAs-GaAs Strained Layer Superlattice

In order to break the ESP limit of AlGaAs-GaAs superlattice, the strained-layer InGaAs-GaAs superlattice was first studied in 1994 by our collaboration (5).

The band splitting between hh- and lh-bands in the well (InGaAs) layer can be introduced by the strain, in addition of superlattice structure effect. An Indium fraction of 15% was chosen to bring a strain of $\sim$1.0 % into the InGaAs layer, and the energy splitting (δ_s) was estimated to be about 30 meV. Four samples with different combinations of surface layer and Be doping density

inside the superlattice structure were made and tested. The highest ESP of 91% was obtained by SLS#4 sample, while the better QE was obtained by SLS#2 sample. Specifications and performances for each sample are listed in Table 2 in section 7.

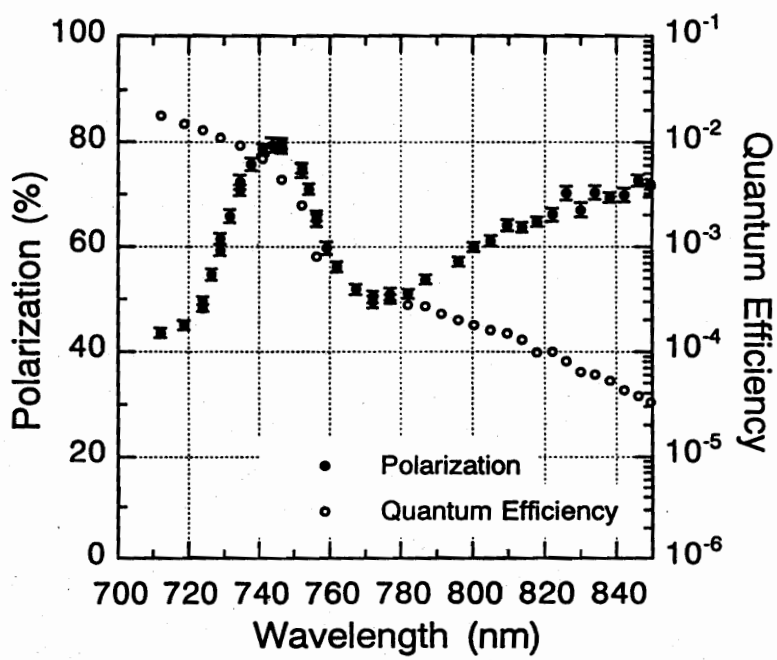
Those results demonstrated that the band mixing between hh- and lh-bands is removed to some extent by the strain, and the ESP higher than 90% can be obtained by this InGaAs-GaAs superlattice. However, the QE is insufficient by more than one order of magnitude compared to that of the AlGaAs-GaAs (SL#7) structure. The reason of this poor QE of InGaAs-GaAs structure is considered as the smaller band-gap than that of AlGaAs-GaAs should bring the smaller magnitude of NEA. This is suggested from several measurements of energy distribution curve of photoelectrons emitted from the NEA surface of GaAs, GaAsP and GaInAsP semiconductors (14).

4. InGaAs-AlGaAs Strained Layer Superlattice

The InGaAs-AlGaAs strained superlattice can have the wider band-gap than that of InGaAs-GaAs, and we started the study of this structure to achieve the QE improvement. Three samples of $In_xGa_{(1-x)}As$-$Al_yGa_{(1-y)}As$ were already made and tested. They have the same fraction parameters of x=0.15 and y=0.35, but different thicknesses of the well (InGaAs) and barrier (AlGaAs) layers.

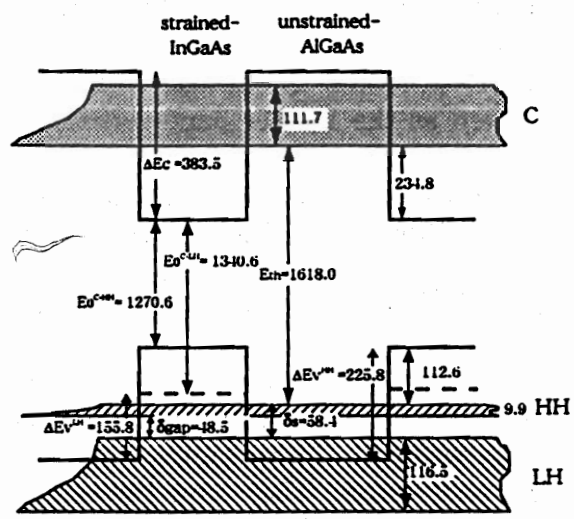
As the best result among them, the maximum ESP of 80% with the QE of 0.7% was achieved at laser wavelength of 741 nm by the SLSA#2 sample, as shown in Fig. 2(a).

Figure 2(a)



The QE is much improved and becomes nearly equal to that of SL#7. However, as a drawback of this (SLSA#2)sample, the maximum ESP is reduced to ~80% from the best value of ~90% of the InGaAs-GaAs sample. The calculated energy band structure (in meV) is shown in Fig. 2(b). It gives the energy band splitting (δ_s) of 58 meV which is much larger than 30 meV of InGaAs-GaAs, and the reason of lower ESP is not yet understood simply.

Figure 2(b)



The properties of this InGaAs-AlGaAs structure is not fully probed until now, and further studies to know the upper limits of ESP, QE and SCL will be continued by samples with different structure parameters (6).

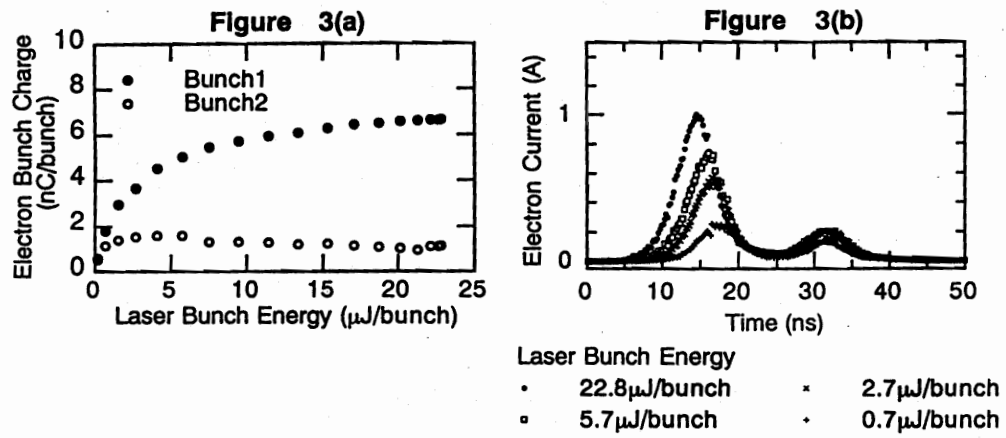
5. Surface-Charge-Limit

The "surface charge limit (SCL)" effect is an important problem, especially for an accelerator which requires the high peak current in a short pulse, such as an electron-positron linear colliders (15). Detailed studies of this effect for photocathodes of bulk-GaAs and strained GaAs layer had been done at SLAC (7)(8). The SCL effect for superlattice photocathode was first studied at SLAC using the SL#7 sample because of its best QE performance. The cathode (20ϕ diameter) was biased at -120 kV (~2.7 MV/m field gradient at surface), and fully illuminated over the cathode area by the 757 nm laser lights. A high charge of 37 nC (2.3×10^{11} electrons) in 2.5 ns bunch was extracted, and this value was consistent with a space charge limitation, that is, no SCL effect was observed (9). From this result, the AlGaAs-GaAs superlattice became a promising candidate of polarized photocathodes for future linear colliders, such as **JLC** and **NLC** which require the beam with several tens of multi-bunch separated by 1.4 ns or 2.8 ns (15).

However, in this SLAC experiment, the test only for single-bunch generation was performed, and that for multi-bunch generation was not done. The test to produce the multi-bunch beam has been continued at Nagoya Univ.

using a 100 kV polarized gun (named as NPES-2) (10). A Nd:YAG pumped Ti:sapphire pulse laser is used to generate a single bunch pulse of Gaussian shape (6 ns FWHM). The double and quadruple bunch pulse are produced by splitting the original pulse, and the bunch spacing is set to be 15 ns and 25 ns, respectively.

First, a thin layer (0.1 μm thickness) of normal GaAs cathode with a Be-doped ($\sim 5 \times 10^{18}/cc$) surface was tested. Results for extraction of 70 keV electron beam are shown in Fig. 3. The laser wavelength was tuned at 780 nm, where the QE was measured to be 0.48%. The charge saturation curve for the first and the second laser bunch is shown in Fig. 3(a), and the electron bunch shapes for various laser powers are shown in Fig. 3(b).



The characteristic features of SCL effect are clearly observed as follows.

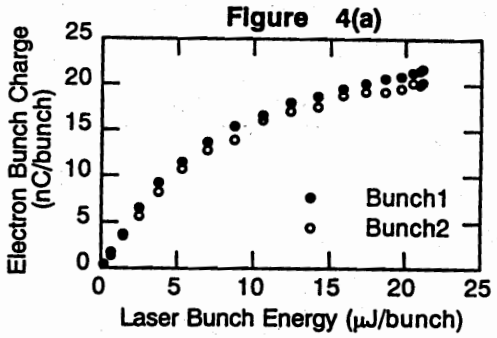
(1) The SCL effect is observed in each pulse in Fig. 3(b). As laser power is increased, the electron bunch shape is deformed from original Gaussian shape and the peak position of the pulse is shifted ahead. The saturated charge ($\sim$7 nC/bunch) of the first bunch in Fig. 3(a) is about a half of the estimated space-charge-limitation of 15 nC/bunch.

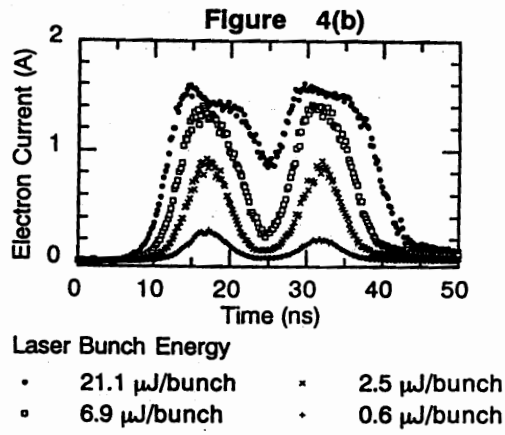
(2) The SCL effect has a longer memory time than the bunch separation of 15 ns. Most of surface charges produced by the first bunch will be still alive until the second bunch illumination takes place, and suppress the escape of the second bunch electrons into vacuum, as suggested in Fig. 3(b). Fig. 3(a) shows only less than 15% of the first bunch charge can be extracted as the second bunch charge.

It is obvious that such a cathode is not useful for multi-bunch generation, and next the AlGaAs-GaAs (SL#7) superlattice with the highly Be-doped ($\sim 5 \times 10^{19}/cc$) surface was tested. Results are shown in Fig. 4, which were taken under the same gun conditions as thin GaAs test. The laser wavelength was tuned at 748 nm, where the maximum ESP of 69% and the QE of 0.65% was

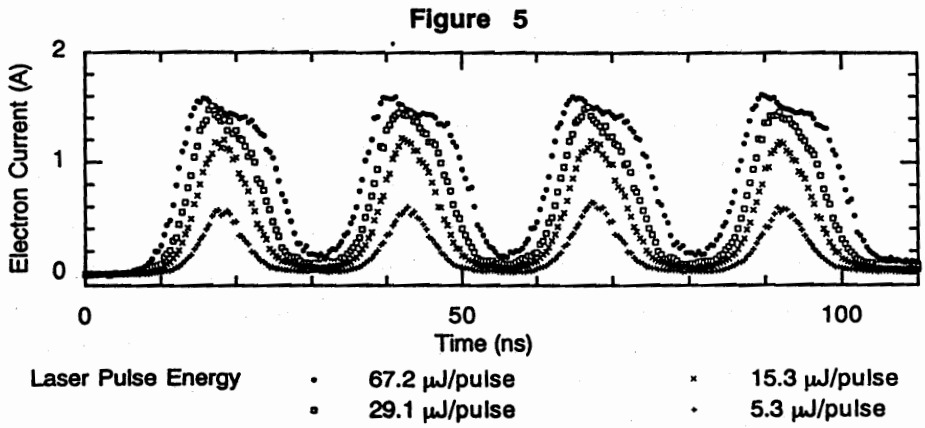
observed. The charge saturation curve for the first and the second laser bunch is shown in Fig. 4(a), and the electron bunch shapes for various laser powers are shown in Fig. 4(b).

As shown in Fig. 4(b), the time shape is not changed both for the first and the second bunch and, the flat-top is observed for higher laser power illumination, which is caused by the space-charge-limitation. It is clearly shown in Fig. 4(a), that there is no suppression for the second electron bunch. The saturated charge level corresponds to ~1.6 A peak current which is consistent with space-charge-limitation.





An extension of this experiment to quadruple bunch generation has been performed, and the electron bunch shapes for various laser powers are shown in Fig. 5. This data also shows that the SCL effect is not observed.



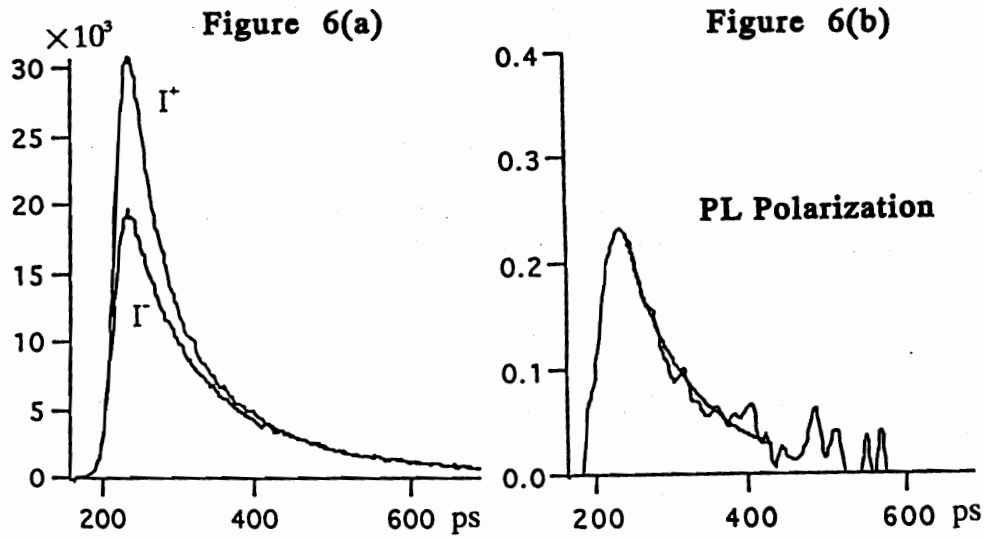
Those data demonstrate the SL#7 cathode is suitable for the multi-bunch generation of high peak current polarized beam. Similar tests are planned for other superlattice to find out which is the essential parameter to remove the SCL effect (10). We expect such a study will lead us to the full understanding

of physical mechanism of SCL effect.

6. Spin Relaxation in Superlattice

Spin relaxation time (T_s) and relaxation time (τ) of electrons in conduction band of superlattice can be simultaneously determined by measuring the time evolution of photoluminescence (PL). Such measurements have been done at Osaka Pref. Univ. using a mode-locked Ti:sapphire laser (2 ps pulse width) and a streak camera ($\pm$8 ps time resolution).

The typical data taken for the InGaAs-AlGaAs (SLSA#2) sample is shown in Fig. 6(a), where I^+, I^- denote left- and right-circulary polarized PL components, respectively. The τ and T_s are determined as a decay constant of total PL intensity and PL polarization (shown in Fig. 6(b)), where they are defined as $(I^+ + I^-)$ and $(I^+ - I^-)/(I^+ + I^-)$, respectively. The results were obtained as $\tau \sim$68 ps and $T_s \sim$85 ps at room temperature.



Results of τ and T_s measurements for three different types of superlattice are listed in Table, 1. From those measurements, it becomes clear that T_s is longer than τ for all samples at room temperature and the T_s can be made much longer by cooling the sample at liquid N_2 temperature. It is also obvious that there is no significant difference in the observed T_s values, in spite of the different ESP observed by the extracted electrons.

Besides of the PL method, the time evolution of the intensity and polarization of the extracted picosecond electron bunch was measured by the radiofrequency streak method at Mainz (16). It will be much interesting to compare both results taken for the same cathode, because the former reflects the τ and T_s of the inside electrons, while the latter reflects those of the escaped electrons.

Table 1: Life-time and Spin-relaxation-time of Superlattice

Crystal Name	Temperature (K)	τ (ps)	τ s (ps)	λ exc (nm)	λ obs (nm)	Electron Polarization
STP#4	R.T.	45	105	780	800~860	80 % (at 880 nm)
	75	77	165			
SL #7	R.T.	69	95	760	780~860	68 % (at 756 nm)
SLS #4	R.T.	61	71	835	870~940	91 % (at 908 nm)
	77	99	229			
SLSA #2	R.T.	68	85	780	800~870	80 % (at 741 nm)

τ : life time of c-band electrons (1997. 8. 1)
τ s : spin relaxation time of c-band electrons
λ exc : wave-length of excitation laser
λ obs : wave-length region of photoluminescence observation
Pol. : the maximum polarization of extracted electrons

7. Discussions

We investigated three different types of superlattice photocathodes. The best achieved performance of these photocathodes in terms of the maximum ESP and the QE at the same laser wavelength are summarized in Table-2, where the various specification parameters are also given.

Making full use of our experimental data, the correlation between the QE and the photon energy which gives the maximum ESP is plotted in Fig. 7.

Figure 7

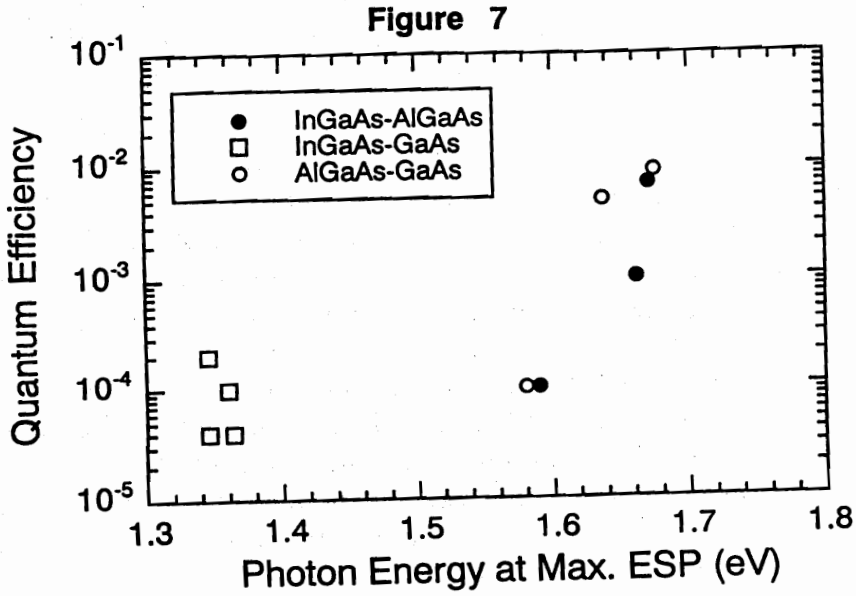


Table 2: Specifications and Performances of $In_xGa_{(1-x)}As$ - $Al_yGa_{(1-y)}As$ Superlattices

(1997. 8. 1)

Crystal Name	x	y	ε (%)	Lw (ML)	L_B (ML)	δs (meV)	Wc (meV)	Surface	Be dope Inside	Be dope Surface	Pol. (%)	Q.E. (%)	λ (nm)
SL #3	0.0	0.35	0.0	7	11	23	89	GaAs	5×10^{18}	5×10^{18}	68	0.01	780
SL #7									5×10^{17}	4×10^{19}	68	0.5	756
SL #11					25	39	10			4×10^{18}	68	0.9	739
SLS #1	0.15	0.0	1.1	7	11	30	191	GaAs	8×10^{16}	4×10^{19}	84	0.01	910
SLS #2								InGaAs	5×10^{17}		88	0.02	920
SLS #3								GaAs			89	0.004	920
SLS #4								InGaAs	8×10^{16}		91	0.004	908
SLSA #1	0.15	0.35	1.1	6	25	82	8	InGaAs	5×10^{17}	4×10^{19}	73	0.1	745
SLSA #2				5	11	58	112				80	0.7	741
SLSA #3				7		73	73				82	0.01	780

x : fraction of Indium
y : fraction of Alminium
ε : strain of InGaAs layer
Lw: thickness of InGaAs (well) layer
L_B : thickness of AlGaAs (barrier) layer

δs : energy splitting between the tops of hh and lh mini-bands
Wc : enegy-broadning of conduction band
Pol. : the maximum polarization
Q.E.: quantum efficiency at the maximum polarzation
λ : laser wavelength which gives maximum polarization

From this plot, we believe we arrive at a conclusion that the wider band-gap superlattice structure is more suitable for the higher QE photocathode.

As a final remark, we consider at moment that the InGaAs-AlGaAs strained layer superlattice is the promising photocathodes due to its potential to provide simultaneously the high ESP, high QE and probably high resistance for SCL-limit. However, the performance limitation is not yet settled rigidly for the superlattice structure, and further studies have enough possibilities to find the best structures for various branches of application.

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