HIGHLY POLARIZED ELECTRONS FROM GaAs-GaAsP AND InGaAs-AlGaAs STRAINED LAYER SUPERLATTICE PHOTOCATHODES

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Abstract

GaAs-GaAsP and InGaAs-AlGaAs strained-layer superlattice photocathodes are presented as emission sources for highly polarized electron beams. The GaAs-GaAsP cathode achieved a maximum polarization of 92(±6)% with a quantum efficiency of 0.5%, while the InGaAs-AlGaAs cathode provides a higher quantum efficiency (0.7%) but a lower polarization (77(±5)%). Criteria for achieving high polarization using superlattice (SL) photocathodes are discussed based on experimental spin-resolved quantum efficiency spectra.

INTRODUCTION

Polarized electron beams are conventionally produced by photoemission from GaAs-type semiconductors. The degeneracy between heavy hole (hh) and light hole (lh) bands at the valence band maximum can be resolved through the use of a strained GaAs layer, a GaAs-AlGaAs superlattice SL layer, or a strained InGaAs-GaAs SL layer, and our group has achieved experimental ESPs of 86% [1], 70% [2] and 83% [3], respectively.

In these studies it became clear that by using a modulation-doping method, the SL cathode is capable of achieving much higher quantum efficiency (QE) than the strained-layer GaAs. Thus, while heavy doping is used for surface layers to achieve large band-bending, medium doping is better for SL layers in order to avoid spin-flip depolarization.

More importantly, however, SL cathodes were found to provide a solution for the surface charge limit (SCL) problem, whereby the maximum current density that can be extracted from the NEA surface is much lower than that determined by the space charge limit. This effect is caused by a decrease in band bending at the NEA surface due to the surface photo-voltage (SPV) effect. However, a GaAs-$Al_{0.31}Ga_{0.69}As$ cathode has been demonstrated to produce a space charge-limited current of 14 A (2.3×10^{11} electrons in a 2.5 ns bunch) using a 120 keV gun with a QE of 2.0% at a laser wavelength of 752 nm [4]. This means that the use of a modulation-doped SL photocathode solves the SCL problem for this beam condition.

Encouraged by these successful results, the present authors have continued research on the development of new types of InGaAs-AlGaAs and GaAs-GaAsP strained SL structures [5]. We have also investigated the SCL problem in more detail using the SL photocathodes irradiated by a nanosecond double-bunch laser with 2.8 ns separation time [6]. In this paper, we describe experimental results demonstrating the improvements in ESP, QE and SCL effect achieved using a GaAs-GaAsP cathode. Criteria for obtaining the highest ESP are also proposed based on the spin-resolved QE spectra.

PHOTOCATHODE PREPARATION

The InGaAs-AlGaAs SL samples were fabricated by molecular beam epitaxy (MBE) at NEC, and the GaAs-GaAsP SL samples were made by metal-oxide chemical vapor deposition (MOCVD) at Nagoya University. The InGaAs-AlGaAs sample was prepared with a protective surface film of amorphous As, which was removed by heat-cleaning at 400 ºC in a vacuum. The GaAs-GaAsP sample had no protective film and was heat cleaned at 550 ºC for 2 h in a vacuum.

A number of different SL samples with various materials and crystal parameters were fabricated and tested, but in this paper, the SLSA#2 and SLSP#9 samples are selected from InGaAs-AlGaAs and GaAs-GaAsP SL families, for detailed analysis. The crystal structure and doping densities for SLSP#9 are shown in Fig. 1.

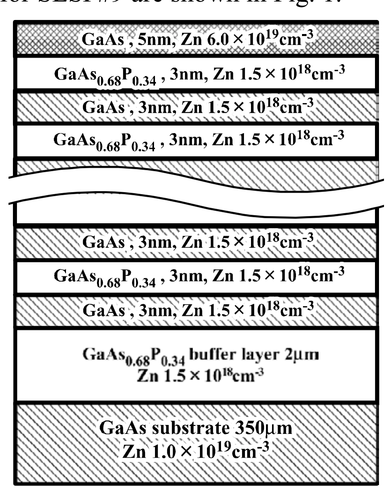

Figure 1: Crystal structure and doping density of the SLSP#9 sample.

A commercially available GaAs wafer with high Zn dopant content was used as a substrate, and a strainrelaxed GaAsP buffer layer was formed on it to obtain large strains for the GaAs well layers. The 16 pairs of SL layers with medium Zn dopings of $1.5\times10^{18}/cm^3$ were terminated with a heavily doped surface layer of GaAs (Zn, $6.0\times10^{19}/cm^3$) to obtain a large band bending at the NEA surface. The crystal structue of SLSA#2 was already given in ref. 6 as a SL-3 sample.

The modulation doping technique was employed for whole samples. The thicknesses of the wells and barrier layers were chosen so as to obtain high large hh-lh energy splitting, and the total thickness of the samples was about 100 nm, set to minimize spin depolarization.

ESP AND QE SPECTRA

ESP and QE spectra were measured using a compact cathode test system with a 4 keV gun and a 100 keV Mott polarimeter [7]. The maximum systematic error for this ESP measurement was estimated to be ±6% (absolute value) [1].

The ESP and QE spectra for the SLSP and SLSA cathodes are shown in Fig. 2 against laser wavelength.

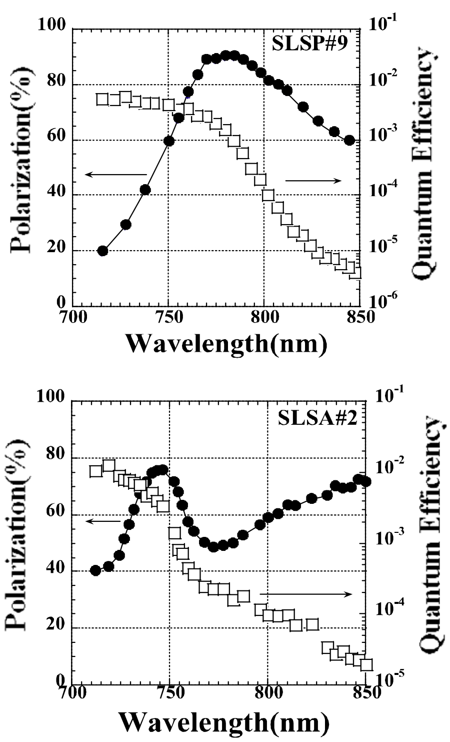

Figure 2: Observed ESP and QE spectra for SLSP#9 and SLSA#2.

Most of the SLSP cathodes achieved maximum ESPs of higher than 90%, with SLSP#9 reaching 92% with a QE of 0.5% at 778 nm. The SLSA cathodes showed lower ESPs of around 80%, but the highest QE of 0.7% was reached by SLSA#2 at 741 nm with an ESP of 77%.

Concerning the SCL effect, we demonstrated that a multi-bunch beam required by a future linear collider can be also produced using the GaAs-GaAsP photocathode in combination with a 70 keV gun and a 0.7 ns double-bunch laser. Recently, this SCL effect was also studied by an approach using core-level photo-electron spectroscopy in combination with synchrotron radiation and a laser. It was found that the SPV effect in the SL cathode is remarkably suppressed compared with that in a bulk-GaAs cathode [8].

DATA ANALYSIS

We have experimentally investigated SL photocathodes with GaAs-AlGaAs, InGaAs-AlGaAs and GaAs-GaAsP structures, and the highest ESPs obtained by these samples are 70%, 83% and 92%, respectively. The maximum ESP depends strongly on the initial polarization (P_i) of excited electrons in the conduction band, and P_i is in turn related to the coefficients of photo-absorption from the hh (A_{hh}) and lh (A_{lh}) mini-bands. The explicit relations are given by $A_{hh} = A_i(1 + P_i)/2$ and $A_{lh} = A_i(1 - P_i)/2$, where A_i is the total absorption coefficient, and the sign of P_i is defined as positive for left-handed electrons.

These photo-absorption coefficients A_{hh} and A_{lh} are proportional to the joint densities of state (JDOS) between conduction and hh or lh bands. The typical behaviors of these JDOSs in the threshold region are shown in Fig. 3, where the two dotted lines represent the JDOSs for strained layers, and the two solid lines denote those for strained SL layers. The latter exhibit a series of quantum jumps with an unit of $m/(\pi\hbar^2)$, where m is a reduced mass defined as $m_{c\text{-}hh} = (m_c\times m_{hh})/(m_c + m_{hh})$ for hh absorption, and $m_{c\text{-}lh} = (m_c\times m_{lh})/(m_c + m_{lh})$ for lh absorption. The width of the absorption edge ($W_{c\text{-}hh}$ or $W_{c\text{-}lh}$) corresponds to the sum of widths for both the conduction and the hh or lh mini-bands.

For comparison of the experimental data with the above JDOS-based A_{hh} and A_{lh} spectra it is convenient to use the spin-resolved quantum efficiencies for left-handed (Q_L) and right-handed (Q_R) electrons in an emitted beam as functions of excitation photon energy. The Q_L and Q_R spectra are related to experimental ESP and QE spectra

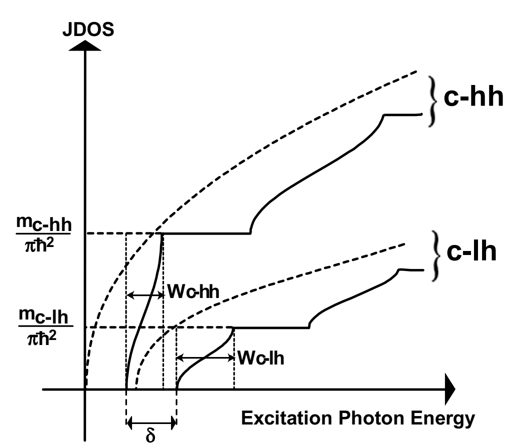

Figure 3: Schematic behaviours of JDOS's as functions of excitation photon energy for strained layer (dotted line) and strained layer (solid line) in threshold energy region.

by $Q_L = QE(1 + ESP)/2$ and $Q_R = QE(1 - ESP)/2$, where the sign of ESP is defined as positive for left-handed electrons.

The experimental Q_L and Q_R spectra are plotted in Fig. 4. As expected from the typical JDOS spectra in Fig. 3, a step-like jump in QE is clearly observed in the Q_L spectra for SLSP#9, yet is difficult to discern for SLSA#2. No such QE steps were observed in any of the Q_R spectra, probably due to the limited range of wavelengths covered by our laser system.

The parameters of the JDOS-based A_{hh} and A_{lh} spectra were determined for the SLSP and SLSA cathodes using threshold energies for hh and lh excitations calculated by the Kronig-Penny (KP) model, by approximating the shapes and widths of the hh and lh absorption edges by dispersion relation curves calculated using the KP model, and by modeling the unit of quantum absorption jump as being proportional to $m/(\pi\hbar^2)$ after the observed jump in QE.

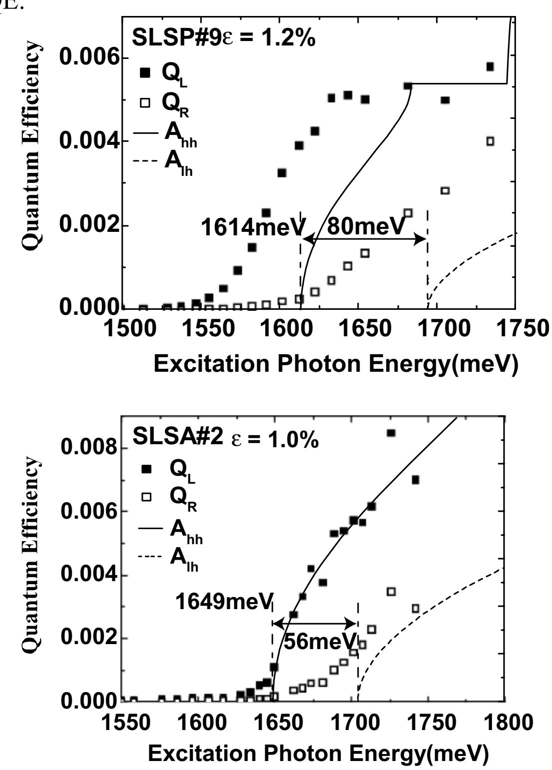

Figure 4: The Q_L and Q_R spectra (experimental) and the JDOS- based A_{hh} and A_{lh} spectra for SLSP#9 and SLSA#2.

The threshold positions for the Q_L and Q_R spectra of SLSP#9 do not coincide with those of the A_{hh} and A_{lh} spectra, instead being shifted to lower photon energies. This discrepancy can be resolved by taking the strain relaxation effect into account. The critical thickness with respect to strain relaxation can be estimated using the Matthews formula. A net strain (ε^*) is defined for the SL layer as $\varepsilon^* = \varepsilon L_w/(L_w + L_b)$, where L_w and L_b are the widths of the well and barrier layers, respectively and ε is the strain induced by lattice-mismatch between the well and barrier layers. The estimated values of strain, net strain and critical thickness are 1.2%, 0.6% and 20 nm. The SLSA sample has a critical thickness about 3 times that for the SLSP cathodes and the strain relaxation seems negligible. As shown in Fig. 5, reasonable agreement is obtained for the threshold positions if the reduced strains after relaxation are assumed to be 0.66% and 0.72%.

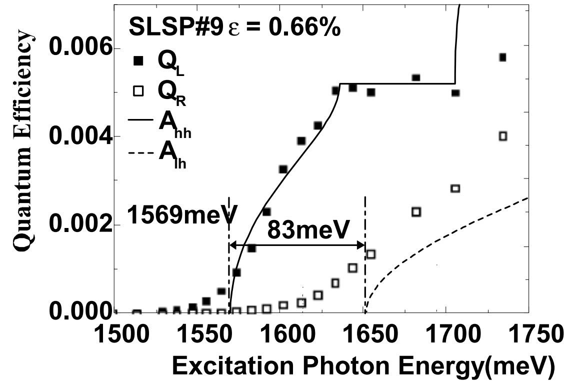

Figure 5: Q_L and Q_R spectra with shifted threshold energies calculated by using the reduced strain for SLSP#9.

Both Q_R spectra show that the threshold position is smeared by small amounts of right-handed electrons below the threshold energy level. These right-handed electrons appear to be created from left-handed electrons through spin-flip interactions, and this smearing effect looks to be an important factor determining the upper-limit of ESP.

SUMMARY

This paper reports our systematic study of strained-layer SL photocathodes with InGaAs-AlGaAs and GaAs-GaAsP structures. Our results confirm that GaAs-GaAsP SL photocathodes are capable of delivering electron beams with high ESP, high QE and high peak current. It is most promising cathode for future linear colliders.

The mechanism that determines the maximum ESP was clarified through phenomenological data analyses of spin-resolved QE spectra. It was found that the most important factors for achieving high ESP are 1) large hh-lh energy (δ) separation, 2) narrow joint widths ($W_{c\text{-}hh}$) between the conduction and hh-band, and 3) minimal depolarization inside the SL layers. Combining 1) and 2), $\delta \geqq W_{c\text{-}hh}$ was derived as the most important condition. The above criteria can explain why the GaAs-GaAsP strained SL photocathode can achieve such high ESP (92%) and QE (0.5%) simultaneously.

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