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Abstract

We have studied the polarization of photoemission from an $\text{In}_{0.15}\text{Ga}_{0.85}\text{As-GaAs}$ strained-layer superlattice. The polarization of $82.7 \pm 0.3(\text{stat.}) \pm 6.1(\text{syst.})\%$ was observed at laser wavelength of from 911 to 916 nm at room temperature. The quantum efficiency at wavelength of 911 nm was measured to be $\sim 0.015\%$ in the vacuum of $\sim 6 \times 10^{-10}$ Torr with cathode high voltage of -4kV.

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Abstract

We have studied the polarization of photoemission from an $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ -GaAs strained-layer superlattice. The polarization of $82.7 \pm 0.3(\text{stat.}) \pm 6.1(\text{syst.})\%$ was observed at laser wavelength of from 911 to 916 nm at room temperature. The quantum efficiency at wavelength of 911 nm was measured to be $\sim 0.015\%$ in the vacuum of $\sim 6 \times 10^{-10}$ Torr with cathode high voltage of -4kV.

KEYWORDS: strained-layer superlattice, polarized electron source, linear collider, charge limit

§1 Introduction

The charged weak bosons (W^+/W^-) couple to only chirality-left quarks and leptons. In high energy interactions of massless limit, the chirality equals the helicity. A polarized electron beam, therefore, can control weak interactions in high energy experiments, and is expected to play important roles in experiments of e^+e^- linear colliders. In the current SLC experiment⁽¹⁾, the polarized electron beam shows its potential role in determination of Weinberg-angle by measuring cross section asymmetry of left- and right-handed electron beam. In experiments at future linear colliders with higher energy, JLC for example⁽²⁾, needs of polarized electron beams will increase much more. In the experiments using polarized electron beams, in most case, the sensitivities of the

experiments increase proportionally to square of the polarization degree. Therefore, a polarized electron source which has as higher polarization as possible is urgently required.

Based on the needs described above, the studies of photocathode material for the polarized electron source have been accelerated in recent 3-4 years. Especially there were breakthrough experiments in early 1991. The strained-InGaAs on GaAs developed by SLAC-Wisconsin-U.C.Berkeley collaboration⁽³⁾ achieved 71% polarization, the AlGaAs-GaAs superlattice developed by KEK-Nagoya-NEC collaboration⁽⁴⁾ achieved also 71%, and the strained-GaAs on GaAsP developed by Nagoya-Daido-OsakaPrefec-ToyotaTech collaboration⁽⁵⁾ achieved 86%. All of above materials were designed to lift heavy- and light-hole degeneracy in valence band; this degeneracy is the reason why conventional GaAs photocathode has the intrinsic upper limit of 50% polarization. Although many of such kind of degeneracy-free-materials have been tested through 1980's⁽⁶⁾, above three experiments firstly showed polarization higher than 50% of electrons extracted in the vacuum. The strained-GaAs on GaAsP, which showed the highest polarization in those three materials, has been successfully used for the current SLC running.

Besides the degree of polarization, an amount of charge which can be extracted from a photocathode is also an important issue. A photocathode used in a linear collider should produce electrons whose intensity is equal or more than that can be accelerated in the collider. This is also a tough requirement for a photocathode. For example the SLC 93 running⁽⁷⁾ requires $\sim 5 \times 10^{10}$ electrons per bunch of 2 ns width at 120 Hz repetition rate. JLC has even more tough requirement for charge⁽⁸⁾. To produce a large number of electrons, the photocathode should have high quantum efficiency, or the photocathode should be irradiated high power laser light if the quantum efficiency of the cathode is not high. However, recent experiments in SLAC⁽⁹⁾ show that the amount of charge does not increase linearly as laser power increases; the increase in the charge shows saturation and finally it reaches the lower level of plateau than that of "space-charge-limit" of the gun. This phenomenon is called "charge-limit" as analogy of "space-charge-limit". The "charge limit" in future linear colliders such as JLC will be much serious than in SLC, therefore further improvement of polarized photocathode is strongly required.

Authors have tested the AlGaAs-GaAs superlattices with various acceptor concentrations, with various surface characters, and with various total thickness⁽¹⁰⁾. Unfortunately none of them gave the polarization higher than 75%. However, one of them, the sample (e) in ref. (10), whose polarization was 71%, gave significantly better quantum efficiency⁽¹¹⁾ compared to other samples. The sample (e), shown in fig. 1, has both of specially designed surface layer and modulation doping (low acceptor concentration interior the cathode and high concentration at the surface GaAs layer of 50Å) to make the good negative-electron-affinity surface. We think this helps much to realize the good

quantum efficiency incorporating with 2-dimensional characteristics of superlattice such as step rising of density of state and enhanced exciton effect. For the test of "charge limit", the sample which had the exactly same structure as the sample (e) was examined by the Gun Test System at SLC in collaboration with SLAC. This sample did not show the "charge limit" phenomenon⁽¹²⁾ and the maximum extracted current reached 2.3×10^{11} electrons in 2.5 n sec, which is equal to the space charge limit of the gun. The quantum efficiency of this sample was measured to be 2%⁽¹³⁾ at the wavelength of polarization maximum in the Gun Test System which had vacuum of $\sim 2 \times 10^{-11}$ Torr with a cathode high voltage of -120kV.

It is important to improve polarization of a superlattice photocathode as high as possible toward 100%, keeping its good quantum efficiency to assure high "charge limit". We thought that the introduction of strain to a superlattice structure will be effective to improve polarization of a superlattice. As a candidate of such material we made a sample of InGaAs-GaAs strained-layer superlattice. The new sample has similar characteristic to the sample (e) employing the modulation doping and the two dimensional superlattice structure. The strain applied on the superlattice has been expected to lift the higher order mixing of heavy-hole and light-hole bands at $k_{\perp} \neq 0$, which is supposed to be the main reason of insufficient polarization of our previous AlGaAs-GaAs superlattices. Thus we had expected that the new sample has quantum efficiency equal to (or better than) that of the sample (e) and has polarization better than all of previous AlGaAs-GaAs superlattices.

§2 Sample Preparation

Our choice of material for the first test is the InGaAs-GaAs strained-layer superlattice grown on a GaAs substrate. The reasons of this choice are followings. Since it is one of most well-studied combination of materials among strained-layer superlattices⁽¹⁴⁾, much data were accumulated, which are necessary to calculate the band structure. Also the know-how of fabrication is well established. If we chose both of Indium fraction and thickness of InGaAs layers in moderate range⁽¹⁴⁾, only InGaAs layers are strained while GaAs layers are strain free since the substrate is GaAs. This condition helps the determination of band-offset, the band structure calculation with small ambiguity, and the growth of high quality superlattice.

The sample was made by molecular beam epitaxy at 520°C. The growth direction is [100]. Figure 2. shows the structure of the sample. The processing steps were as follows. A GaAs buffer layer of 500Å thickness was grown on a GaAs substrate to obtain a flat surface. Next an $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ buffer layer of 1μm thickness was deposited to provide high quality surface for growth of the strained-layer superlattice on it⁽¹⁵⁾. (Note the lattice constant of AlGaAs is equal to that of GaAs within an accuracy

of practical point of view.) Then layers of GaAs (31.1Å thickness) were interleaved with layers of $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ (20.0Å thickness) until the total thickness reached 919Å (18 periods). Next a GaAs surface layer of 50Å was grown. Finally, an As cap of $\sim 2\mu\text{m}$ thickness was grown at -14 °C to protect the surface against the atmosphere. All of GaAs, InGaAs, and AlGaAs layers except the substrate were p-doped with Be.

The concentration of the acceptors in the surface 50Å-GaAs layer is very high, $3.9 \times 10^{19} \text{ cm}^{-3}$, to achieve the good negative-electron-affinity. On the other hand, that in the other part of the superlattice is rather low, $7.8.2 \times 10^{16} \text{ cm}^{-3}$, to get small band tails and small spin relaxation. In this condition, a calculation shows that the region of the band bending at the surface is confined in the surface GaAs layer of 50Å.

§3 Band Structure and Choice of Parameters

Firstly, we discuss the band discontinuities between two host materials, GaAs and $\text{In}_x\text{Ga}_{1-x}\text{As}$, caused by strain, based on a paper by Pan et al⁽¹⁶⁾. The formation of the mini-bands by the periodic potential of the superlattice structure will be discussed later.

If only $\text{In}_x\text{Ga}_{1-x}\text{As}$ layers are strained, the biaxial strain ϵ in them is estimated to be -1.06% from eq. (1) of ref. (16). This strain changes the band gaps of InGaAs; the strain dependent energy gap between the heavy-hole band and the conduction band ($E_0^{\text{C,HH}}$), and that between the light-hole band and the conduction band ($E_0^{\text{C,LH}}$). See equation (2) of ref. (16).

In our case, InGaAs layers sustain a biaxial in-plane compression ($\epsilon < 0$), the strain effect increases the average of the heavy- and the light-hole gaps relative to the conduction band. In addition the strain removes the degeneracy between the heavy-hole band and the light-hole band at Γ point so that the former moves up and the latter moves down relative to the average of them. In this case $E_0^{\text{C,HH}}$ is smaller than $E_0^{\text{C,LH}}$, and the band offset ratio Q_C is defined as,

$$Q_C = \Delta E_C / (E_0(\text{GaAs}) - E_0^{\text{C,HH}}),$$

where the quantity ΔE_C denotes the discontinuity of the conduction band. Once Q_C is given from experimental data, the band discontinuities of the heavy- (ΔE_V^{HH}) and light-holes (ΔE_V^{LH}) are calculated by following equations,

$$\Delta E_V^{\text{HH}} = E_0(\text{GaAs}) - \Delta E_C - E_0^{\text{C,HH}},$$

$$\Delta E_V^{\text{LH}} = E_0(\text{GaAs}) - \Delta E_C - E_0^{\text{C,LH}}.$$

The Indium fraction (x) of 0.15 in our sample is chosen to satisfy following conditions. Firstly, x should not be too large to keep strain on InGaAs layer to be in moderate (1-2%) range⁽¹⁴⁾ which assures high quality sample with less dislocation. From this condition, the maximum value of x is confined around 0.3. Secondly it is obvious if x is too small, the strain effect is not significant. Furthermore, for the x value smaller than 0.1 the various experiments gave inconsistent values of Q_C which range from 0.40 to 0.83. On the other hand, if x is larger than 0.1 most of experiments show consistent values which are $0.7 \pm 0.1^{(17)-(20)}$. With the x value of 0.15, $\text{In}_x\text{Ga}_{1-x}\text{As}$ (GaAs) layers work as wells (barriers) for both of conduction band electrons and heavy-holes, while for light-holes $\text{In}_x\text{Ga}_{1-x}\text{As}$ (GaAs) layers work as barriers (wells).

$E_0^{C,HH}$ and $E_0^{C,LH}$ are calculated by using eqs.(2)-(4) and parameters in table I of ref.(16),

$$E_0^{C,HH} = 1271 \quad (\text{meV}),$$

$$E_0^{C,LH} = 1341 \quad (\text{meV}),$$

where $E_0(\text{GaAs}) = 1420 \text{ meV}$ is used.

By employing $Q_C = 0.7$, band discontinuities are calculated as follows at $T = 300\text{K}$,

$$\Delta E_C = 105 \quad (\text{meV}),$$

$$\Delta E_V^{HH} = 45 \quad (\text{meV}),$$

$$\Delta E_V^{LH} = -25 \quad (\text{meV}).$$

The thicknesses of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ and the GaAs layers in the superlattice are decided to satisfy following conditions. Firstly the thickness of a GaAs layer should be larger than that of a $\text{In}_x\text{Ga}_{1-x}\text{As}$ layer. This is necessary to keep the GaAs layers to be strain free. Secondly, the thickness of a $\text{In}_x\text{Ga}_{1-x}\text{As}$ layer should be smaller than the critical thickness ($\sim 90\text{\AA}$) estimated by the equation of Matthews and Blakeslee⁽²¹⁾. Thirdly the thickness of a GaAs layer, this is a barrier for conduction band electrons, should not be too large to give the reasonable mobility for conduction band electrons to the direction to penetrate the superlattice layers⁽²²⁾. We choose the thickness of a GaAs layer to be $31.1\text{\AA}$ (11 monolayers) and that of a $\text{In}_x\text{Ga}_{1-x}\text{As}$ to be $20.0\text{\AA}$ (7 monolayers).

These values are forced to coincide with those of the AlGaAs-GaAs superlattices of our previous experiments in the unit of monolayers; the thickness of the well (InGaAs) layers for the conduction band electrons in the InGaAs-GaAs superlattice is chosen to be same as that (the thickness of GaAs layers) in the AlGaAs-GaAs superlattice. (Note that GaAs layers are well layers in a AlGaAs-GaAs superlattice.) This coincidence seems useful to make the comparison between the new sample and our previous superlattices.

The mini-bands are calculated using the envelope-function approximation by Bastard⁽²³⁾ (eqs.(12)-(14) of ref. (23)). We assume $k_{\perp}^2 = 0$ for simplicity. Effective masses employed in the calculation are given as follows:

$$m_{C}^*(\text{In}_x\text{Ga}_{1-x}\text{As}) = (0.0665 - 0.044x)m_0,$$

$$m_{HH}^*[100](\text{In}_x\text{Ga}_{1-x}\text{As}) = (0.33 + 0.07x)m_0,$$

$$m_{LH}^*[100](\text{In}_x\text{Ga}_{1-x}\text{As}) = (0.090 - 0.062x)m_0,$$

where m_0 is the free electron mass. An effective mass of conduction band electrons is taken from eq. (5a) of ref. (16). Hole effective masses are determined so that it agrees with those in GaAs given in ref. (24) when x is set to be zero. The dependence on x is determined to reproduce the difference between effective masses in GaAs and those in InAs given in the table 1-I of ref. (20). Figure 3 shows the result of the calculation. The resultant energy split (δ_s) between the heavy-hole and the light-hole mini-bands is 30 meV. Here the split is defined as the difference between the top of the heavy-hole and the top of the light-hole mini-bands.

§4 Experimental Results and Discussions

We measured the electron polarization by means of the Mott analyzer at Nagoya University⁽²⁵⁾. Firstly, the As cap for surface passivation was removed by heat cleaning ($400^\circ\text{C}/30\text{minutes}$) in ultra-high vacuum before we started polarization measurement. Cesium gas and Oxygen gas were used to activate the surface of the superlattice. The polarization measurement was done at room temperature. A description of the method to determine the polarization appears in a previous report⁽⁴⁾. The base pressure around the cathode was $\sim 6 \times 10^{-10}$ Torr. The high voltage applied on the photocathode was -4kV .

Figure 4 shows electron spin polarization as a function of laser wavelength. Three series of measurements, indicated by the marks of open circles ($\circ$), close circles ($\bullet$) and open squares ($\square$) were performed. A heat cleaning and a re-activation for negative-electron-affinity were done between any of two series. Results of three series of measurements are consistent as shown in the figure. Statistical error of each point is typically $\pm 0.9\%$. An uncertainty in the Sherman function contributes an additional error which was estimated to be 7.4% ⁽²⁶⁾ of the measured polarization. This uncertainty is common to all measurements. The maximum polarization of $82.7 \pm 0.3(\text{stat.}) \pm 6.1(\text{syst.})\%$ was observed at laser wavelength of from 911 to 916 nm. The typical quantum efficiency was measured to be 0.015% (0.029%) at $\lambda = 911\text{nm}$ (847nm) and the typical extracted current was 1000nA (DC).

The measured maximum polarization is significantly better than that of all of our previous AlGaAs-GaAs superlattices and is same level as that of the best strained-GaAs on GaAsP. Thus one of our expectation is verified.

However the measured quantum efficiency is one order of magnitude smaller than that of the sample (c) in the same condition of vacuum. We guess the reason of this low quantum efficiency of the new sample is that, (1) the surface layer (GaAs) is the

barrier layer, or (2) there is too large jump of acceptor concentration between the inside and the surface layer which cause Fermi-level bump near the surface, or combination of both (1) and (2). For the test of above points to improve quantum efficiency, we plan to test new samples which have moderate jump of acceptor concentration and which have a surface layer of well material.

§5 Summary

The polarization of photoemission from a $\text{In}_{0.15}\text{Ga}_{0.85}\text{As-GaAs}$ strained-layer superlattice has been firstly measured. The polarization of $82.7 \pm 0.3(\text{stat.}) \pm 6.1(\text{syst.})\%$ was observed at laser wavelength of from 911 to 916 nm at room temperature. The quantum efficiency at wavelength of 911 nm was measured to be $\sim 0.015\%$ in the condition of vacuum of $\sim 6 \times 10^{-10}$ Torr. Though the achieved polarization is higher than that of all of our previous $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As-GaAs}$ superlattices, the quantum efficiency is not good enough as we expected. We concern the surface barrier layer of 50Å or the Fermi-level bump caused by modulation doping may obstruct electron escape to the vacuum. Thus we think the quantum efficiency of the $\text{In}_{0.15}\text{Ga}_{0.85}\text{As-GaAs}$ strained-layer superlattice can be improved by adjusting modulation of acceptor concentration and by choosing thickness/material of the surface layer.

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Figure Captions

- Fig.1 The structure of the sample (c) of the $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ -GaAs superlattice in our previous experiment. The polarization of the sample was 71%. Note that GaAs and $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ are well and barrier material, respectively, for all of heavy-holes, light-holes, and conduction band electrons. The As passivation layer was removed by the heat cleaning in the gun. Interior concentration of $4.8 \times 10^{17} \text{cm}^{-3}$ is the average of that in the GaAs layers and of that in the $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ layers.
- Fig.2 The structure of the sample of the InGaAs-GaAs strained-layer superlattice. The As passivation layer was removed by the heat cleaning in the gun.
- Fig.3 The calculated band structure (in meV) of the InGaAs-GaAs strained-layer superlattice. The hatched area marked C, HH, and LH represent the conduction, heavy-hole, and light-hole mini-bands, respectively. Solid (dashed) line represents the band gap edges of conduction and heavy-hole (light-hole) of host material.
- Fig.4 Measured spin polarization of the InGaAs-GaAs strained-layer superlattice as a function of laser wavelength. Statistical error of each point is typically $\pm 0.9\%$.

Figure 1

Figure 2

Figure 3

Figure 4