Large Enhancement of Polarization Observed by Extracted Electrons from the AlGaAs-GaAs Superlattice

T. Omori,[1] Y. Kurihara,[1] T. Nakanishi,[2] H. Aoyagi,[2] T. Baba,[3] T. Furuya,[1] K. Itoga,[1] M. Mizuta,[3] S. Nakamura,[2],[a] Y. Takeuchi,[1] M. Tsubata,[2] and M. Yoshioka[1]

[1]*KEK, National Laboratory for High Energy Physics, Oho 1-1, Tsukuba-city, Ibaraki-ken, 305 Japan*

[2]*Faculty of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya-city, Aichi-ken, 406 Japan*

[3]*Fundamental Research Laboratories, NEC Corporation, Miyukigaoka 34, Tsukuba-city, Ibaraki-ken, 305 Japan*

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We have observed a large enhancement of the spin polarization of electrons extracted from an AlGaAs-GaAs superlattice illuminated by circularly polarized light. A polarization of 71.2 $\pm$ 1.1(stat) $\pm$ 6.1(syst)% was obtained with a photon wavelength of 802 nm at room temperature. We have also confirmed the removal of the degeneracy between a heavy-hole band and a light-hole band at the Γ point from the laser-wavelength dependence of the polarization.

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Introduction.— Recently, the desire for developing a highly polarized electron source has been increasing in high-energy physics [1], especially for applications to linear colliders such as the JLC. A GaAs photocathode with a negative-electron-affinity (NEA) surface illuminated by circularly polarized light is the standard method to produce an intense beam of polarized electrons. The intrinsic upper limit of polarization for a GaAs photocathode is 50% because of the degeneracy between the heavy- and the light-hole bands at the Γ point. An AlGaAs-GaAs superlattice has been studied as a possible electron source with polarization greater than 50%, due to the removal of the degeneracy by the periodic potential wells in the superlattice. However, none of the experiments performed in the 1980s [2] achieved a polarization of extracted electrons greater than 50%. The reasons for the low polarization were assumed to be the depolarization of the electron spin before emission, the lack of a large separation between the heavy- and the light-hole bands, or a combination of both. Recently, we observed an enhancement of the spin polarization slightly higher than 50% by using a 0.4-μm-thick superlattice consisting of alternate layers of $Al_xGa_{1-x}As$ (31.1 Å thick and $x=0.35$) and GaAs (19.8 Å thick) [3]. SLAC-Wisconsin-UC Berkeley-CEBAF group [4] also reported an enhancement which was slightly higher than 50% by using an AlAs-GaAs monolayer superlattice. However, the achieved polarizations in both experiments were still not high enough to justify the use of superlattices. In our previous sample, three parameters of the superlattice (the thickness of the GaAs and AlGaAs layers and the fraction of aluminum in AlGaAs) were chosen to give a large enough energy splitting between the heavy- and the light-hole bands compared to the thermal noise and to get a large transition rate between neighboring layers [5]. From the data of this sample we concluded that the energy splitting was large enough to excite the heavy-hole band only. However, depolarization inside and/or on the surface of the superlattice yielded only a small enhancement of the polarization of the extracted electrons. In order to test this conclusion, we have prepared a superlattice with the same parameters except for the total thickness. The total thickness of the new sample was chosen to be a factor of 4 thinner than that of the previous one in order to reduce the depolarization inside it. In this article we report the results of polarization measurements on this thinner sample.

Experiment.— The superlattice sample was grown by molecular-beam epitaxy (MBE) at a temperature of 520 °C (Table I). As a first step in making a flat surface, a GaAs buffer layer of 500 Å thickness was grown on a GaAs substrate. Next, an AlGaAs barrier layer with 1 μm thickness was inserted to avoid electron emission from the GaAs substrate, which has polarization lower than 50%. Then a superlattice layer of 0.1 μm was grown. The thickness of each GaAs layer and AlGaAs layer was 19.8 and 31.1 Å, respectively. The superlattice had twenty wells. The aluminum fraction was set to be 35%. The thicknesses of GaAs (AlGaAs) layers were chosen to satisfy two contradicting requirements; that the energy splitting be larger than thermal noise (26 meV) at room temperature and that the conduction-band electrons still have large transition rates to neighboring layers [5]. The energy splitting is defined as the distance between the upper bound of the heavy-hole band and that of the light-hole band. The energy splitting of the sample was calculated to be 44 meV. The top layer of the superlat-

TABLE I. Structure of the sample.

As ($\sim$2 μm, for surface passivation)
Be-doped AlGaAs-GaAs superlattice (0.1 μm)
Be-GaAs (19.8 Å: 7 monolayers, $p=6.2\times10^{18}/cm^3$)
Be-$Al_{0.35}Ga_{0.65}As$ (31.1 Å: 11 monolayers, $p=4.0\times10^{18}/cm^3$)
Be-doped $Al_{0.35}Ga_{0.65}As$ (1 μm, $p=5.0\times10^{18}/cm^3$, for barrier)
Be-doped GaAs buffer layer (500 Å, $p=7.7\times10^{18}/cm^3$)
Zn-doped GaAs substrate [400 μm, $p=2.0\times10^{19}/cm^3$, orientation: (100)]

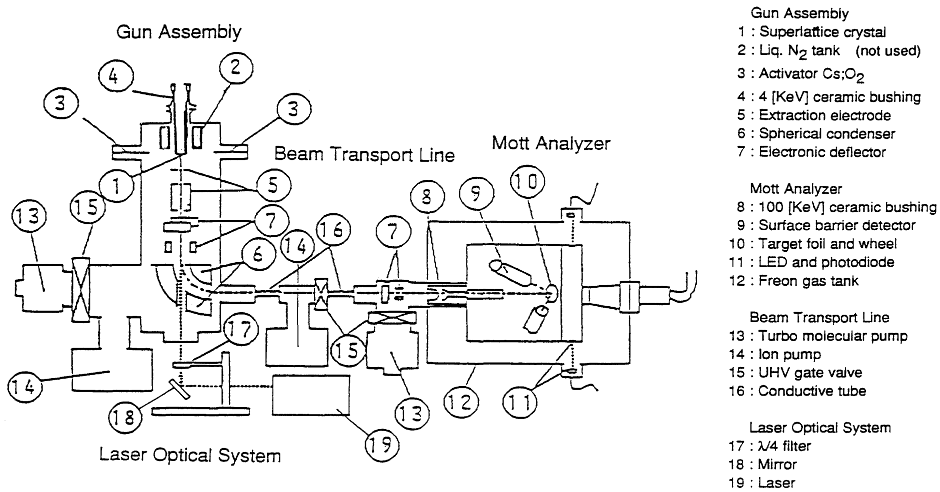

FIG. 1. The schematic view of the polarization measurement apparatus at Nagoya University.

tice was a GaAs layer whose thickness was the same as inside the superlattice. The superlattice surface was covered by an As cap of about 2 μm thickness grown at $-3\,°C$ for protection against the atmosphere. All of the GaAs and AlGaAs layers except for the substrate were heavily Be doped ($\sim 5\times 10^{18}/cm^3$) to get a negative-electron-affinity surface.

The apparatus [6] to measure the electron-spin polarization is shown in Fig. 1. It consisted of a gun and a Mott polarization analyzer. The base pressure of the gun was 1.1×10^{-9} torr. The cw titanium:sapphire laser, excited by an argon laser, with a quarter-wave plate supplied circularly polarized monochromatic photons. The range of tunable wavelengths was $\lambda = 700$–870 nm. The electrons were accelerated up to 100 keV and injected into the Mott analyzer, then they were scattered by the Au foil supported by a thin Formvar backing of thickness less than 50 $\mu g/cm^2$. Five Au foils with thicknesses of 184, 251, 574, 962, and 1137 Å were used in order to measure an effective Sherman function. The foil thicknesses were measured by backward Rutherford scattering of $^4He^+$ particles with an accuracy of 7%. The electrons scattered at angles of $\pm 120°$ were detected by two Si surface-barrier detectors which were located on the right and left sides of the beam line. Cesium gas was used to activate the surface of the superlattice making it an NEA surface. Before the NEA activation, the As cap was removed by heat cleaning for 30 min at a temperature of 400 °C in an ultrahigh vacuum. No damage of the superlattice structure was observed after the heat cleaning [5].

An example of the energy spectrum of scattered electrons is shown in Fig. 2 for the Au foil of 962 Å thickness. To determine the number of single elastic scatterings, we have to subtract background events from the distribution. For the signal, a Gaussian distribution was assumed, for the background, two kinds of functions were examined: (1) $ax+b$ and (2) $a/\{\exp[-(x-x_0)^2/b^2]+1\}$. In the latter case, x_0 was chosen to be the same as the mean of the Gaussian distribution of the signal. The background function (2) simulates a flat distribution below x_0 smeared by the detector resolution. The measured energy spectrum was fitted by the Gaussian distribution plus the background function, as shown in Fig. 2. In all of the spectra, the background (2) gave a smaller χ^2.

The left-right asymmetry was measured for three

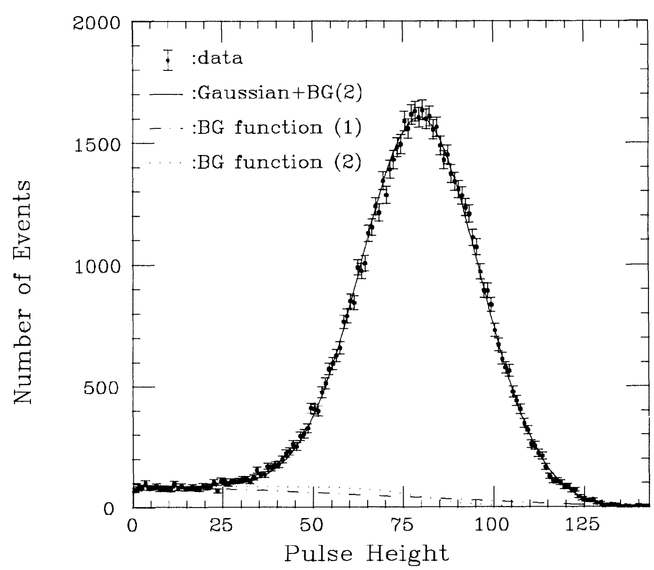

FIG. 2. An example of the energy spectrum of scattered electrons by an Au foil with thickness of 962 Å. The solid line shows the fitting function sum of the Gaussian distribution and the background function (2). The deviation of the fitting result employing the background function (1) from the solid line was small. The dashed (dotted) line shows the background function (1) [(2)].

different photon polarization states, linear, left handed, and right handed. The asymmetries with left-handed laser light and those with right-handed laser light were calculated independently. In this independent calculation, the measurement with linearly polarized photons was used to correct for the asymmetry of the acceptance of the two silicon detectors. It was checked that the left-handed and the right-handed measurements were consistent with each other to within the error. The final results of the asymmetry were calculated from both the left-handed measurement and the right-handed measurement under the assumption that the absolute value of polarization with left-handed light was equal to that with right-handed light (the measurement with linearly polarized light was not used). This method minimized the systematic error from the acceptance correction.

We measured the left-right asymmetry with five foils as shown in Fig. 3, where a laser wavelength of $\lambda = 792$ nm and the background function (2) were used. The asymmetry at the zero-thickness point which corresponds to a pure single scattering, was found to be 0.275 ± 0.024 by a linear fitting of the above data, because the left-right asymmetry is inversely proportional to the thickness of thin Au foils within practical accuracy. The error is the quadrature sum of the error of the linear fitting, the deviation due to the choice of the background function, and the error due to the measured accuracy of the Au foil thickness. The polarization at $\lambda = 792$ nm was calculated to be $69.2 \pm 6.0\%$ from the asymmetry divided by the Sherman function at zero thickness (0.397). From the above fitting, the effective Sherman function at $t = 962$ Å was calculated to be 0.218 ± 0.019.

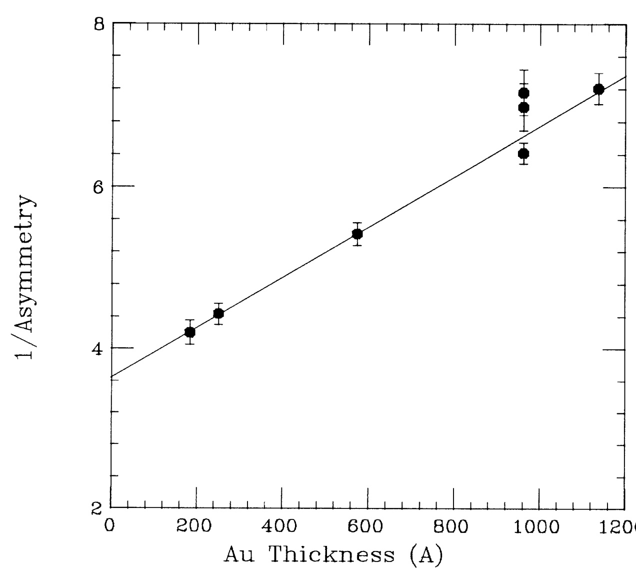

FIG. 3. Reciprocal of the left-right asymmetry of the scattered electrons as a function of Au thickness. The solid line shows the results of the linear fitting.

Figure 4 shows the electron-spin polarization as a function of laser wavelength measured with the 962-Å Au foil. The indicated error for each point is the statistical error only. The uncertainty of the estimation of the effective Sherman function should be included to obtain the total error. Two series of measurements, indicated by solid circles and open squares in Fig. 4, were performed. A heat cleaning and a NEA reactivation were performed between the two series. The results were consistent with each other to within errors. The electron-spin polarization seems to step up from the lower level of ~40% to the higher level of ~70%. An interpretation of this behavior is that the higher level around $\lambda = 780$–800 nm is due to electrons excited from the heavy-hole band only, while the lower level around $\lambda = 700$–740 nm is due to electrons excited from the heavy-hole and light-hole bands. A maximum polarization of $(71.2 \pm 1.1 \pm 6.1)\%$ was obtained at $\lambda = 802$ nm, where the first (second) error indicates the statistical (systematic) one. The typical quantum efficiency was measured to be 2.1×10^{-4} (2.7×10^{-6}) at $\lambda = 772$ nm (802 nm). The typical extracted current was 50 nA (dc).

Summary.— We have observed that a superlattice photocathode can overcome the 50% limit of spin polarization. A polarization of $[71.2 \pm 1.1(\text{stat}) \pm 6.1(\text{syst})]\%$, which is the best value for solid-state photocathodes, was obtained at room temperature. The removal of the degeneracy between the heavy- and light-hole bands at the Γ point was confirmed from the laser wavelength dependence of the polarization. Our previous sample [3], which had the same superlattice parameters except that total thickness of the superlattice layer, 0.4 μm, was 4 times thicker than the present one, gave a polarization of 53%. By comparing the previous result with the present one, we have confirmed that depolarization inside the superlattice is one of the essential causes of the

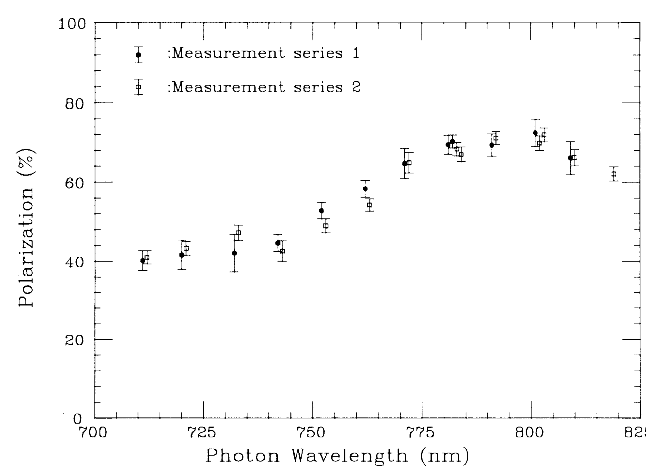

FIG. 4. The measured electron spin polarization as a function of the wavelength of the laser light. The two series of measurements were consistent with each other.

suppression of the polarization of extracted electrons.

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[a]Now at Physikalisches Institut der Universität Bonn, Bonn, Germany.

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