Spin-Polarized Electrons Extracted from GaAs Tips using Field Emission

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Abstract. A pyramidal shaped GaAs (tip-GaAs) photocathode for a polarized electron source (PES) was developed to improve beam brightness and negative electron affinity (NEA) lifetime by using field emission. The emission mechanism also enables the photocathode to extract electrons from the positive electron affinity (PEA) surface, and relax the NEA lifetime problem. I-V characteristics of electrons extracted from tip-GaAs shows that the electron beam was extracted by field emission mechanism, because a linear dependence was obtained in Fowler-Nordheim (F-N) plot. Furthermore, a tip-GaAs cathode has succeeded in generation of spin polarized electron beam. The polarization degree of tip-GaAs is about 34% at excitation photon energy of 1.63eV which is no less than that obtained by an NEA-GaAs cathode.

Keywords: spin-polarization, field emission, NEA surface, photocathode, depolarization
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INTRODUCTION

Strained-layer superlattice structures have been presenting the most promising performance as a photocathode for the polarized electron source (PES). In our experiments, the GaAs-GaAsP photocathode achieved maximum polarization of 92±6% with quantum efficiency of 0.5%, while the InGaAs-AlGaAs photocathode provided higher quantum efficiency (0.7%) with lower polarization (77±5%). Criteria for achieving high spin polarization and high quantum efficiency using superlattice photocathodes were clarified by employing the spin-resolved quantum efficiency spectra [1-3].

However, it seems that major problems remained for the PES R&D are to improve (1) beam emittance and (2) NEA lifetime under gun operations for high peak current and high average current, respectively. In order to overcome these problems simultaneously, we started a development of a new type photocathode using field emission mechanism. First, we tried to use a pyramidal shape GaAs (tip-GaAs). Using the tip-GaAs, electrons can be emitted from a small area at the top of pyramid, and

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thus the beam emittance is expected to be small. This emission mechanism also enables to extract electrons from the poor NEA or small PEA surface into vacuum, and it helps to relax the NEA lifetime problem. This is the standard font and layout for the individual paragraphs.

EXPERIMENT

photocathode

The pyramidal shaped GaAs was fabricated from the Zn-doped GaAs (100) substrate by anisotropic wet etching using H_3PO_4 solutions [4]. For GaAs etching, resist-mask patterns were prepared on the GaAs substrates by photolithography. The resist pattern was square, and length of side was 10μm. The edge of the square mask was aligned along the <010> direction. In order to sharpen the tip-radius, the GaAs etching was carried out in a $10H_3PO_4$:H_2O_2:H_2O solution at –1 ^oC. As shown in Fig. 1, a tip radius was about 25 nm, and a distance between tip to tip was 200 μm. After this process, tip-GaAs was rinsed by a HCl-isopropanol treatment for removing gallium and arsenic oxides from the surface [5].

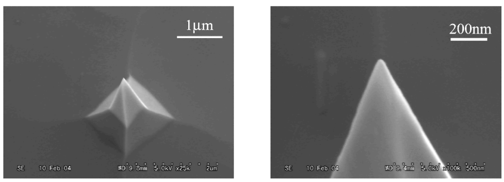

FIGURE 1. SEM images of tip-GaAs fabricated by anisotropic wet etching

Instruments

In this experiment, we used 20-kV DC gun for detailed measurements of field emission current, and 70-keV PES for spin polarization measurement. The reason to use the 20-kV DC gun is that the 70-kV DC gun can not apply enough high electric field to measure the field emission characteristics from tip-GaAs. Conversely, ESP measurement was taken by 70-keV PES, because the 20-kV DC gun did not have a spin polarization analyzer. This equipment was maintained under UHV (10^{-9} Pa) conditions to create a NEA surface. Each chamber was evacuated by an ion pump and non-evaporable getter (NEG) pump. The 20-kV gun is schematized in Fig. 2.

The electrodes were made of stainless steel 316L since it has a relatively low carbon content which can cause a site of field emission of dark current. For surface polishing, electrochemical etching and buffering were employed simultaneously to obtain a mirror-flat surface. The photocathode sample was attached to a molybdenum stage, and heated using a rod heater to remove the arsenic layer and obtain a clean surface. Cesium was evaporated from a commercially available dispenser that was placed in front of the cathode by a manipulator during the cesiation process. Oxygen was introduced into the gun chamber from a pure oxygen tank through a variable leak valve. The gap separation between cathode and anode was variable since the anode was supported by a manipulator equipped with a viewing port. Circularly polarized light was directed into the photocathode surface through the viewing port. This apparatus could supply a high-gradient dc electric field of 4.8 MV/m to the photocathode surface because the gap separation of the electrodes and applied voltage were 3.2 mm and 20 kV, respectively, under conditions where the dark current did not exceed 0.1 nA despite the amount of cesium deposited on the cathode during the many cesiation processes. The electric field is smaller than the value of dividing the voltage by the gap, because the geometry of electrodes is not flat plate. The actual electric field was estimated by using the electromagnetic simulation code POISSON with the electrodes' geometries and dimensions.

The 70-keV PES was composed of a 70-kV DC gun and spin polarization analyzer. The spin polarization measurement system contains a Wien-filter and Mott scattering polarization analyzer (Mott-polarimeter). The DC gun of PES is designed to use a photocathode which is illuminated with a laser light. The electron beam generated at the DC gun is transferred to the Mott-polarimeter through the Wien-filter. This apparatus is described in more detail in Ref. 3.

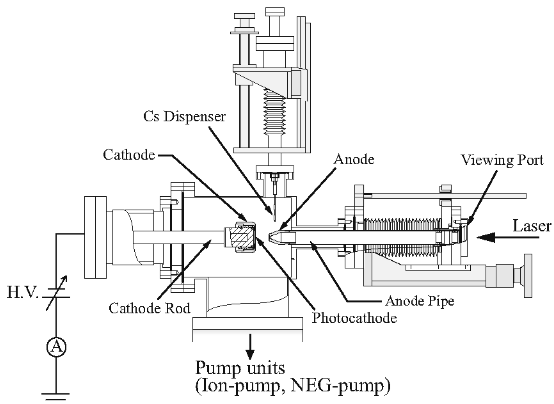

FIGURE 2. Schematic of 20-kV DC gun.

RESULTS

I-V characteristics were measured by a 20-kV DC gun under illuminating circularly polarized light. Figure 3 (a) shows the Fowler-Nordheim (F-N) plots of the emission current obtained by laser light irradiation at a wavelength of 780 nm. The F-N plot is the two dimensional plot of $\ln(I/E^2)$ versus $1/E$, where I is an emission current and E is an electric field, and often used for prediction of a field emission phenomenon. The solid lines in Fig. 3 (a) show the least-squares fits of the experimental data. The two plots showed the difference in the QE results. These plots had a similar slope, but the extracted current density was different. Thus, the two fitting lines had the same slope because the coefficient of enhancement factor of these shapes was the same. The slopes of the fitting lines were $(1.4\pm0.6)\times10^7$ and $(1.4\pm0.2)\times10^7$ in SI units.

The QE spectrum of tip-GaAs under high dc gradient was measured. Figure 3 (b) shows QE as a function of excitation photon energy under a high gradient field of 2.9

MV/m; the applied voltage and electrode gap were 20 kV and 5.34 mm, respectively. The solid line is the fitting curve obtained through a calculation of tunneling yield based on the WKB approximation. The QE rose rapidly at 1.6 eV, which did not correspond to the band-gap energy of GaAs. The QE of NEA-GaAs increased more gradually, which was reflected in the joint density of state.

ESP measurements of tip-GaAs were made by a Mott-polarimeter with a 70-kV DC gun. Figure 4 shows the ESP and QE of tip-GaAs under a high applied gradient field and concurrent irradiation with a circularly polarized laser light. For clarifying these ESP measurement conditions, each QE which was taken together with the ESP measurement by the 70-keV PES is plotted in concern with the horizontal axis. The ESP curve for tip-GaAs shows a bumpy profile between 20 % and 38 % with an excitation photon energy of 1.44 eV to 1.77 eV. Furthermore, the ESP spectrum has higher values than that of NEA-GaAs in the photon energy range above 1.61 eV. This energy range corresponds to the rising edge of QE at 1.6 eV. This photon energy also coincided with the value of Fig. 3 (b).

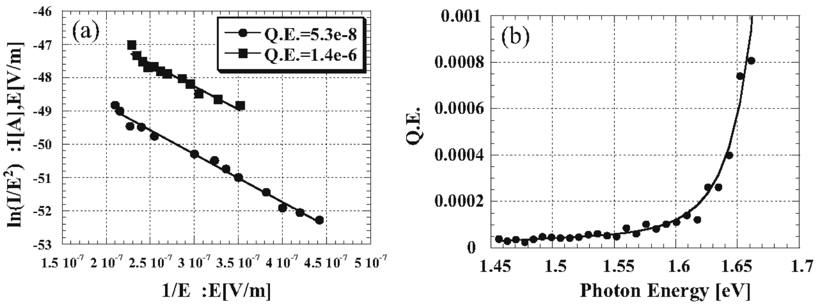

FIGURE 3. (a) F-N plot of photo-electron extracted from yip-GaAs, (b) QE of tip-GaAs under applying high gradient field as a function of excitation photon energy.

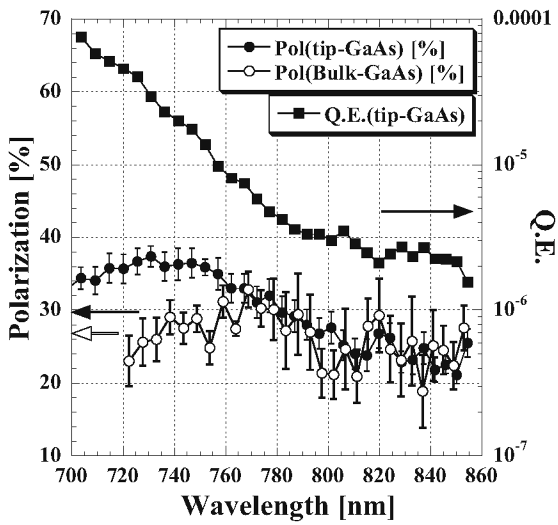

FIGURE 4. ESP and QE of tip-GaAs as a function of wavelength.

DISCUSSION

We analyzed the results with the extraction process model shown in Fig. 5. The combination of the axis in F-N plot is derived from Fowler-Nordheim equation. In Fig. 3 (a), the data could be well fitted by the straight line. Hence, the proportional behavior to the F-N plot suggests that excited electrons were extracted into vacuum by the tunneling effect. Furthermore, an electron affinity can be also calculated from the slope of the fitting curve in the F-N plot. From this equation, the electron affinity is estimated to be $(1.6\pm0.5)\times10^{-2}\beta^{2/3}$ using the slope of the fitting curve in Fig. 3 (a), which was taken to be $(1.4\pm0.5)\times10^{7}$ in the present calculation. The magnitude of β depends on the geometry and demensions of the cathode. For a tip curvature of 50 nm and a tip-to-tip distance of 200 μm, the field enhancement factor β of tip-GaAs is estimated to be 66 by using the simulation code POISSON. In this estimation, electric field infiltration into the semiconductor is not considered because of the high p-doping density. Hence, the electron affinity of tip-GaAs was estimated to be 0.26±0.08 eV.

The fitting curve by the WKB approximation in the QE spectrum of Fig. 3 (b) can be expressed as

$$T(\varepsilon_z) = \exp\left[-\frac{4\sqrt{2m}}{3\hbar eE}\left(\chi-\varepsilon_z\right)^{3/2}\right] \tag{1}$$

Here, T is the tunneling yield, ε_Z the electron energy, m the electron mass, and e the elementary electron charge. Considering the correspondence of the fitting curve in Fig. 3 (b), the rapid rise reflects a surface tunneling effect. Thus, the phenomena demonstrated that excited electrons were extracted by the field emission mechanism. Subsequently, from the result of QE spectrum, the electron affinity was also estimated by WKB approximation fitting. Taking the band-gap energy of GaAs at 300 K to be 1.43 eV, the electron affinity is estimated to be 0.23±0.01 eV from the fitting curve parameter [6]. This estimate is in good agreement with the estimate obtained by the F-N plot. Thus, the two estimations based on the tunneling effect are consistent with each other, which indicates clearly that the spin-polarized electrons were extracted by field emission. Furthermore, the relation between the I-V characteristics and the QE spectrum was established.

In Fig. 4, the ESP data at tip-GaAs surface condition had a difference from NEA surface condition in wavelength region under 760 nm. In order to understand these phenomena, we considered the depolarization mechanism in GaAs crystal and extraction mechanism. While drifting to the surface, partial excited electrons are scattered by holes, phonons, and so on. When the electrons excited above the bottom of the conduction band, the energy dispersion will be widen, and the low energy end of this wide dispersion has a lower polarization compared to the initial polarization. Since the tunneling yield of surface increases at a rapid rate for electron energy, electrons transmitting into a vacuum constitute the majority of high-energy end of wide dispersion. Therefore it would appear that the low-polarization portion is cut off, and high-polarization portion can only extract into vacuum [7].

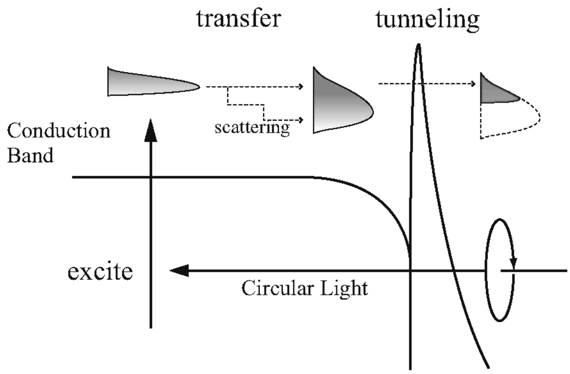

FIGURE 5. Schematic of one-dimensional potential model of field emission in p-doped semiconductor. The magnitude of polarization is indicated by the light and shaded regions under the energy distribution curve, where darker shades correspond to higher polarization.

CONCLUTION

We have demonstrated that spin polarized electrons can be extracted from tip-GaAs by using a field emission mechanism under circular light irradiation. The polarization degree of tip-GaAs is about 34% at excitation photon energy of 1.63eV which is no less than that obtained by an NEA-GaAs cathode. Furthermore, distinctive phenomena caused by field emission were observed in the ESP and QE spectrum. It is hoped that this photocathode will be widely applicable to accelerators analytical instruments.

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