Superlattice Photocathode for High Brightness and Long NEA-surface lifetime

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Abstract. We have suggested using a superlattice semiconductor instead of a bulk semiconductor as an NEA-photocathode for small emittance and high quantum yield because the mini-band energy width and high joint density of states at the bottom of the conduction band can bring small photoelectron’s momentum spread and high quantum yield at excitation energy of the band gap. We developed the test sample of the AlGaAs-GaAs superlattice semiconductor designed by using Klonig-Penny-Bastard model. The obtained quantum yield spectrum from the AlGaAs-GaAs superlattice semiconductor after NEA-surface activation was a step function of excitation photon energy most likely caused by the quantum confinement effect.

1. Introduction

Photocathodes using semiconductors made of GaAs and related materials with negative electron affinity surfaces (NEA-GaAs) have high quantum yield and can emit spin-polarized electrons excited by a circular polarized laser. NEA-GaAs photocathodes using semiconductors with a strained-layer structure or strained-layer superlattice structure [1] [2] [3] have played a very important role as highly spin-polarized electron sources in high-energy physics [4]. An NEA-GaAs with a bulk structure has also been used as a photocathode which can extract large photocurrent (9mA) for a free electron laser accelerator [5].

The key phenomenon of photocathodes using semiconductors made of GaAs and related materials with negative electron affinity surfaces (NEA-GaAs) is that the NEA surface enables excited electrons in the bottom of the conduction band to escape to a vacuum. However, the surface of conventional NEA-GaAs photocathodes is damaged by back bombardment of ionized residual gas by photoelectrons [6]. The decrease in quantum yield due to the damage to the surface results in a short lifetime during high-photocurrent operation. The conventional NEA-GaAs photocathode with high-brightness beam performance uses a GaAs semiconductor with a bulk structure. However this photocathode has a trade-off in beam performance between the small energy spread of electrons and high photocurrent, because it requires higher-energy photons to achieve high-photocurrent operation at the expense of a larger energy spread of electrons.
We considered that the optimum electron affinity of a semiconductor is essential for improvement of the decrease in quantum yield due to damage to the surface. To confirm this hypothesis, we developed AlGaAs photocathodes with various Al fractions. Those AlGaAs samples achieved a 10-times-longer quantum yield life than the GaAs sample, and had longer quantum yield life by larger Al fraction [7].

2. Superlattice Photocathode

Semiconductors for a highly spin-polarized electron source require that the splitting energy between the heavy- and light-hole energy levels (hh-lh splitting energy) in the valence band is as high as possible. Superlattice photocathodes with a large hh-lh splitting energy in the valence band are known to be a spin-polarized electron source with polarization above 50% [1]. We also considered that semiconductors with a superlattice structure convey the advantages not only for highly spin-polarized electron sources but also for high-brightness electron sources.

We consider that the superlattice semiconductor has intrinsic advantages for an NEA-GaAs photocathode with higher quantum yield, smaller energy spread of photoelectrons and longer NEA lifetime than conventional NEA-GaAs photocathodes owing the following two factors. (1) The electron energy density of state (DOS) for a superlattice is a step function of excitation photon energy due to the quantum confinement effect as shown in Figure 1. In a NEA-GaAs photocathode, the quantum yield is proportional to the ratio of DOS integrated from the band-gap energy to the excitation photon energy [8]. A GaAs semiconductor with a bulk structure, which has a monotonically increasing DOS function, requires higher-energy photons to achieve high quantum yield operation at the expense of a large energy spread of electrons. A superlattice photocathode, on the other hand, enables the achievement of high quantum yield and small energy spread ($\Delta E_{CB}$) simultaneously by choosing excitation photon energy ($E_{g}^{SL}$) immediately above the step energy of DOS. (2) Larger band-gap energy and smaller electron affinity of the superlattice semiconductor than those of GaAs semiconductor are possible by optimization of semiconductor materials and a superlattice structure. Experimental results of polarized electron sources have suggested that a semiconductor with larger band-gap energy is more suitable for producing a photocathode with high quantum yield [9]. A semiconductor with smaller electron affinity is more suitable photocathode with an NEA surface for maintaining an NEA state for a longer time, because the semiconductor can has larger energy difference between vacuum level and the conduction band minimum when the surface of the semiconductor is activated to the NEA surface [7].

To optimize the superlattice structure for a small energy spread of photoelectrons, we calculated the energy width of the conduction mini band for various AlGaAs-GaAs superlattice structures using the Klonig-Penny-Bastard model [10]. From these results we could observe that AlGaAs-GaAs superlattice structures with Al fraction = 0.29, the well layer thickness below 6 nm and the barrier layer thickness over 6 nm enable energy width of the conduction mini band to be smaller than the thermal energy at room temperature [11].

3. Experimental

In order to confirm small energy spread of photoelectrons from a superlattice photocathode, we decided to develop an AlGaAs-GaAs superlattice semiconductor and measure the dependence of quantum yield on the excitation energy by using the photocathode test system at RIKEN.
3.1. AlGaAs-GaAs semiconductor sample

| Layer          | Thickness | Doping Density |
|----------------|-----------|----------------|
| Surface layer  | GaAs, 5nm | Be \(2 \times 10^{18} \text{cm}^{-3}\) |
| Superlattice   | Al\(_{0.29}\)GaAs (barrier), 2nm, \(2 \times 10^{18} \text{cm}^{-3}\) |
|                | GaAs (well), 6nm, \(2 \times 10^{18} \text{cm}^{-3}\) |
| Barrier layer  | Al\(_{0.29}\)GaAs, 100nm, \(2 \times 10^{19} \text{cm}^{-3}\) |
| GaAs substrate | 300\(\mu\)m, Zn \(2 \times 10^{18} \text{cm}^{-3}\) |

Figure 2. Crystal structure and doping densities of the AlGaAs-GaAs superlattice semiconductor test sample.

Figure 2 shows the design parameter of the crystal structure of the AlGaAs-GaAs superlattice semiconductor used in this study. A commercially available GaAs wafer with Zn doping of \(2 \times 10^{18} \text{cm}^{-3}\) was used as a substrate. The thickness of the GaAs well layer is 2nm and the thickness of the AlGaAs barrier layer with Al fraction of 0.29 is 6nm. The 380 pair of the well and barrier layer with Be doping of \(2 \times 10^{18} \text{cm}^{-3}\) is terminated with a heavily doped surface layer of a GaAs (Be \(2 \times 10^{19} \text{cm}^{-3}\)) to suppress the surface charge limit phenomenon [12]. The superlattice semiconductor is prepared with a protective surface film of amorphous Arsenic, which is removed by annealing at 400 degree in a vacuum. The superlattice semiconductor was fabricated by molecular-beam epitaxy at Venture Business Laboratory of Nagoya University.

Figure 3 shows the energy band structures of the superlattice semiconductor. The energy band structures were obtained from a calculation using the Kronig-Penny-Bastard model. The estimated band gap energy (1.65 eV), which is the energy separation between the bottom of the minimum conduction mini-band (CB1) and the top of the maximum valence mini-band, is larger than that of GaAs (1.43 eV [13]). The electron affinity (\(\chi = 3.92\)eV) is smaller than that of a GaAs (4.07eV [14]). The energy width of the CB1 is 25meV correspond to the thermal energy at 300K.

3.2. Photocathode test system

The dependence of the quantum yield of the superlattice semiconductor after NEA activation on the excitation energy is measured by using the photocathode test system shown in Figure 4. The system consists of the extremely high vacuum chamber for the NEA-surface activation and a YAG-laser-pumped Ti:Sapphire tuneable wavelength laser.

A base pressure of the extremely high vacuum chamber was \(5 \times 10^{-10}\)Pa. In the extremely high vacuum chamber, small amounts of caesium and oxygen were alternatively supplied to obtain NEA surface after the semiconductor is heat-
cleaned to remove the protective surface film of amorphous arsenic at 400°C for 1 h. A commercially available dispenser of the caesium source is on the front of the cathode holder. Oxygen is introduced into the gun chamber from a pure oxygen bottle through a variable leak valve. The quantum yield is monitored by a simultaneous measurement of photocurrent and irradiation laser power. A 633nm He-Ne CW laser is used as the light source to monitor the photocurrent during the NEA activation process, where the semiconductor is biased at -100 V. The YAG-laser-pumped Ti:Sapphire laser is used as a light source with tuneable wavelength for the measurement of the dependence of the quantum yield on the excitation energy, where the semiconductor is biased at -500 V. Extracted average photocurrent during the measurement of the dependence of the quantum yield on the excitation energy is below 5nA which is enough small to avoid serious the space charge limitation effect shown in Figure 5.

4. Result and Discussion

Figure 6 shows the result of quantum yield depend on the excitation energy for the AlGaAs-GaAs superlattice semiconductor after the NEA surface activation. The spectrum has two steps which have the peaks at 1.68 eV and 1.74 eV. It seems that the quantum yield peak around 1.68 eV is the spectrum by photoelectrons excited to the CB1 from HH1 and LH1 band, and the quantum yield peak around 1.74 eV is the spectrum by photoelectrons excited to the CB1 from the HH2 band. The spectrum around those peaks can be caused by the CB1 with energy width of 25meV, because quantum yield at 1.64eV is higher 4 times than that at 1.67eV and quantum yield at 1.72eV is higher 4 times than that at 1.75eV. The quantum yield at 1.68 eV is $1.1 \times 10^{-4}$, the quantum yield at 1.74 eV is $2.8 \times 10^{-4}$. These very low quantum yields compared with that of the conventional GaAs photocathode around band gap energy are probably caused by an NEA-surface activation of a poor quality.

5. Conclusions

We considered that a superlattice semiconductor can be more suitable a photocathode for small energy spread of photoelectrons and high quantum yield. We developed the AlGaAs-GaAs photocathode with Al fraction of 0.29, the barrier layer with the thickness of 6nm and the well layer with the thickness of 2nm, and measured the dependence of quantum yield on the excitation energy for the AlGaAs-GaAs superlattice semiconductor test sample after NEA-surface activation. The obtained quantum yield spectrum was a step function of excitation photon energy most likely caused by the quantum confinement effect. Momentum of excited electrons can redistributed during emission through the surface band bending region. If the redistribution could be avoided by a suitable design of the surface region, we conclude that the AlGaAs-GaAs superlattice semiconductor is a suitable NEA-
GaAs photocathode which fulfils the requirements of smaller energy spread of photoelectrons than that of the conventional bulk-GaAs photocathode.

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