ELECTRON BEAM GENERATION FROM InGaN/GaN SUPERLATTICE PHOTOCATHODE

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Abstract

Longer spin relaxation time for a cubic-GaN sample compared with a GaAs sample is expected, and electron spin polarization (ESP) is strongly depended on the spin relaxation time. As a future polarization source, feasibility studies for a hcp-GaN sample as a polarized electron source were carried out instead of a cubic-GaN. In our experiments, the hcp-GaN sample with negative electron affinity surface was obtained by deposition of small amounts of Cs. The quantum efficiency of 1% was obtained with the pump laser wavelength of 405 nm. A dark lifetime improvement for the hcp-GaN sample comparison to a GaAs-based sample was also observed. Furthermore, it is confirmed that the ESP value for the hcp-GaN sample was almost zero. This result could be understood by considering the spin relaxation time of the hcp-GaN, and considered to be improved by using the cubic-GaN.

INTRODUCTION

A brightness electron beam with highly electron spin polarization (ESP) is required for various applications such as high energy physics [1, 2] and electron microscopes [3, 4]. For these purposes, the brightness of 2×10^7 A/cm^2/sr was demonstrated [3] by using GaAs based transmission type superlattice (SL) photocathode (PC), and the ESP of 92 % and the quantum efficiency (QE) of 1.6 % were simultaneously achieved by using the strain-compensated GaAs/GaAsP SL sample with the SL thickness of 192 nm [5].

By using the strain-compensated technique, the GaAs/GaAsP SL samples with thickness of up to 720 nm were grown with well crystalline condition, and the QE improvement was successfully observed [5]. However, the ESP limitation due to the spin relaxations during electron diffusion in the semiconductor was also noted [6]. Then, in order to achieve highly ESP vaules and higher QE simultaneously by increasing the SL thickness, the PCs with longer spin relaxation times should be employed.

Concerning the spin relaxation time, a factor of 20 times longer spin relaxation time compared the conventional GaAs samples was reported for a cubic-GaN sample [7]. Then we decidecd to investigate the feasibility of GaN-based PCs. However, unfortunately the cubic-GaN sample was not able to obtain in crystallizing problems. The hcp-GaN sample was tested as a prior study.

In this study, the hcp-GaN/InGaN SL sample was activated by small amounts deposition of Cs and the negative electron affinity (NEA) surface was obtained. The QEs and vacuum lifetime are detailed in this paper.

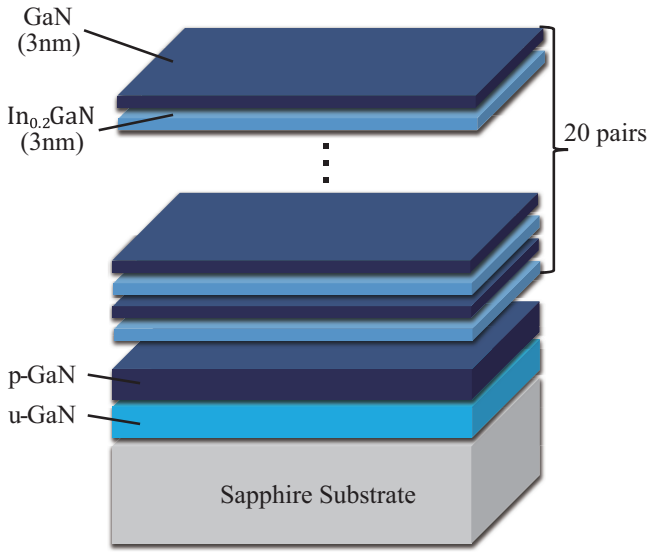

Figure 1: Schematic image of GaN/InGaN photocathode sample.

SAMPLE AND CATHODE PREPARATION

The schematic image of the experimental PC sample is shown in Fig. 1. The sample was fabricated by metal-oxide chemical-vapor deposition and purchased from the Semiconductor Company POWDEC K.K.. A 20-pair strained SL structures of the hcp-GaN and the $In_{0.2}GaN$ layers was employed as the active layer. The thickness of both SL layers were 3 nm and Mg doping of 3×10^{19} cm^{-3} were accumulated. The SL layers were grown on a p-GaN, a undoped-GaN and a 430-μm thickness sapphire substrate.

The energy band structure of the hcp-GaN/InGaN PC sample is shown in Fig. 2. The SL thickness and the crystal ratio of indium to gallium of the sample were determined in consideration of the band gap energy and energy splitting between the heavy- and light-hole mini bands in the valence band. The band gap energy was estimated to be 2.78 eV. The band gap energy corresponds to the pump laser wavelength of 446 nm. To confirm the band gap energy and to evaluate the crystalline quality, photoluminescence (PL) measurement was carried out at room temperature. As the results, the peak PL intensity was obtained at 446.5 nm with the FWHM band width of 20.7 nm. This band width is considered to be not inferior as compared with GaAs-based PC samples.

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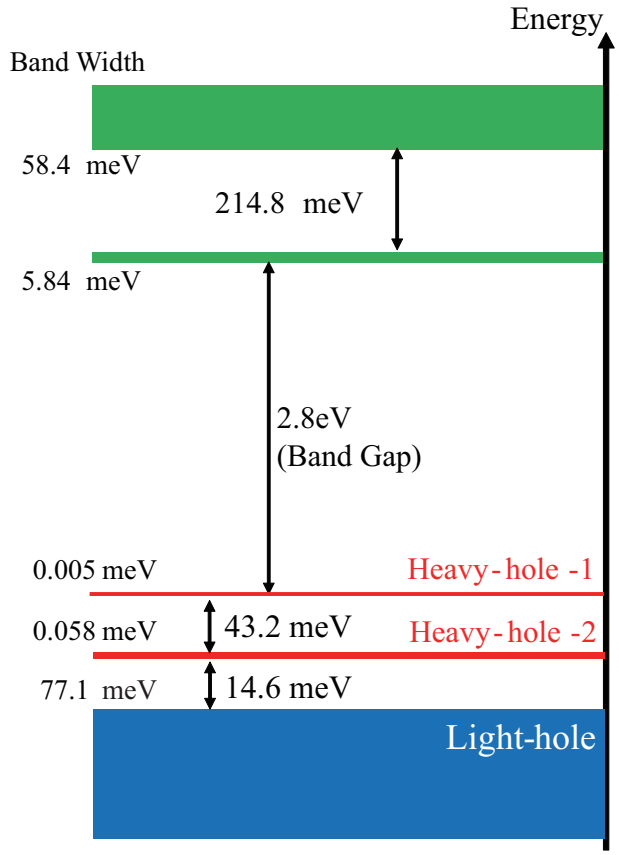

Figure 2: Energy band structure of the GaN/GaInN PC sample.

The band splitting between the heavy- and light-hole mini bands could be also estimated from Fig. 2. It is found that the two-different heavy-hole mini bands exists above the highest light hole mini band in the valence band. The band splitting energy of 57.8 meV could be estimated as the energy between the light-hole mini band and the higher energy heavy-hole mini band that represents "Heavy-hole-1" in Fig. 2. It is considered that this band splitting energy is enough to obtain highly ESPs at the conduction band. However due to short spin relaxation time of 0.47 ps for the hcp-GaN sample [7], the ESP for a electron beam extracted from the sample to the vacuum was estimated to be around zero.

EXPERIMENTAL RESULTS

Surface Activation

The PC sample was cut to squares 10-mm on a side from the two-inch substrate in the atmosphere. The cut sample was fixed on a molybdenum puck and installed to an electron gun without any additional cleaning process. Measurements were carried out using the transmission-type 20-kV electron gun [3], consisting of a surface activation chamber with a load lock system, and combined with a Mott polarimeter.

For the surface cleaning, the sample was heat cleaned around 480 °C in the activation chamber. After the sample was naturally cooled down to the room temperature, the sample was activated by deposition of small amounts of Cs. The QE in the reflection mode was monitored by simultaneous measurements of photocurrent (total current emitted from the cathode) and laser irradiation power. The base pressure of the activation chamber was below 8×10^{-8} Pa and the pump laser wavelength of 405 nm was chosen in the activation process.

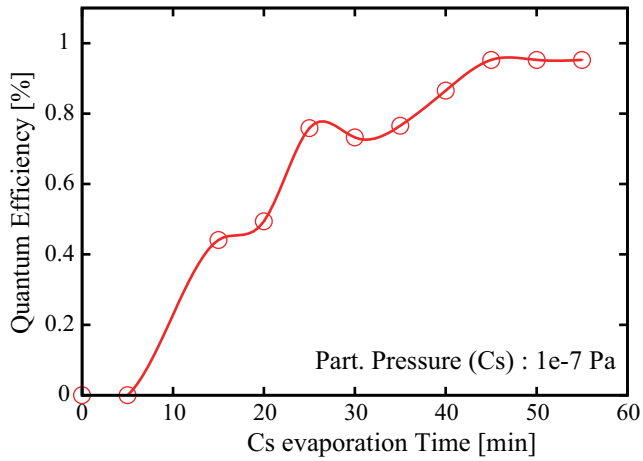

Figure 3: Quantum efficiencies as a function of Cs deposition time during the surface activation process.

The QEs as a function of Cs deposition time during the surface activation process are typically shown in Fig. 3. In the activation process, the partial pressure of the Cs was kept around 1×10^{-7} Pa by controlling the load current for the Cs dispenser. We repeated the surface cleaning and activation several times. The obtained maximum QEs were around 1% at the laser wavelength of 405 nm. We also tried to activate the sample by alternate deposition of small amounts Cs and O_2 during the surface activation process, so-called "Yo-Yo method". Although the QE decreases for O_2 deposition just after Cs deposition and the QE recovery by following Cs deposition instead of O_2 were observed, the distinct QE improvement was not observed.

Electron Polarization

The ESP was measured using a standard 100 kV Mott polarimeter [8]. A 90 ° bend spherical condenser was used to change the longitudinal spin polarization to a transverse polarization. The systematic error for the ESP measurement was estimated to be 6%.

For the ESP measurements, the electron beam was extracted by transmission mode of the electron gun, which the pump laser was injected from the backside of samples and electron beam was extracted from the front side. The pump laser with the wavelength of 453 nm was obtained by using a laser diode and the photon energy was slightly smaller than the band gap energy.

The measured ESP values of 0.13% was obtained. This result is consistent with the estimation value from the spin relaxation and electron diffusion in the hcp-GaN sample.

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Dark Lifetime

The dark lifetime was also measured for the activated GaN/InGaN sample. In the measurement, the base pressure was around 1.2×10^{-9} Pa and the electrode voltage was set to be 0.6 kV. The QEs were measured regularly with a certain interval and the extraction current was set down to 60 nC in the QE measurement. The measurement was made with transmission mode of the electron gun.

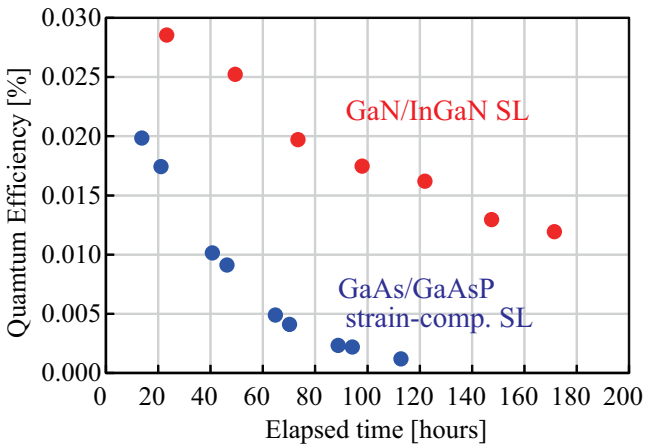

Figure 4: Quantum efficiencies as a function of the elapsed time after the activation. The result for the GaN/InGaN SL sample (red) was compared with that for the GaAs/GaAsP strain-compensated SL sample (blue).

The measurement result of the QE degradation for the GaN/InGaN SL sample (red) was shown comparing with that for the GaAs/GaAsP strain-compansated SL sample (blue) in Fig. 4. The obtained initial QEs for both samples were relatively small due to some trouble with the activation system. The pump laser wavelength of 453 and 785 nm was chosen for the GaN/InGaN and GaAs/GaAsP samples, and both laser energies were slightly small for the energy band gaps.

The dark lifetimes were evaluated from the plotted data's by fitting exponentially decay function. The $1/e$ lifetimes for the GaN/InGaN and the GaAs/GaAsP samples were estimated to be 162 and 37 hours, respectively. Then it seems that the GaN/InGaN has the longer lifetime than the GaAs/GaAsP samples.

CONCLUSION

The hcp-GaN/InGaN SL sample was carried out for feasibility studies as a future polarized electron source application. The NEA-activation was carried out by deposition of small amounts Cs and the QE of around 1% was obtained with the pump laser wavelength of 453 nm. The activation procedure was not optimized in our experiments due to some activation system troubles, then some possibilities for QE improvement remain.

As the results, the relative higher QE and the longer dark lifetime are expected for the GaN PCs compared with the GaAs-besed PC. Therefore, GaN-based PCs are considered to become one of candidate technologies for the future polarized sources after further developments and efforts.

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