Status of the high brightness polarized electron source using transmission photocathode

N. Yamamoto¹, X.G. Jin¹, A. Mano¹, T. Ujihara¹, Y. Takeda¹, S. Okumi², T. Nakamichi², T. Yasue³, T. Koshikawa³, T. Ohshima¹, T. Saka⁵, and H. Horinaka⁶

¹Graduate School of Engineering, Nagoya University, Nagoya, Japan
²Graduate School of Science, Nagoya University, Nagoya, Japan
³Osaka Electro-Communication University, Osaka, Japan
⁴Central Research Laboratory, Hitachi Ltd., Tokyo, Japan
⁵Daido Institute of Technology, Nagoya, Japan
⁶Faculty of Engineering, Osaka Prefecture University, Osaka, Japan

E-mail: naoto@nagoya-u.jp

Abstract. Recently, we have developed a transmission-type polarized electron source (PES) for the generation of a high brightness beam. The developed PES can applied the extraction voltage of 20 kV at 4 mm electrode-gap and enables to realize the source beam radius of a few micrometer. As the results of prototype gun experiments, the brightness of $2 \times 10^7$ A.cm$^{-2}$.sr$^{-1}$ and a charge density lifetime of $1.8 \times 10^8$ C.cm$^{-2}$ were obtained. A maximum polarization of $90\%$ and quantum efficiency of $0.09\%$ was achieved simultaneously using the transmission photocathode with GaAs-GaAsP strained superlattice layers. Up to now, another two electron gun was manufactured, and those mechanical designs are almost same as that of the prototype. The prototype gun and the second gun have been already operated for the photocathode R&D and for the Spin-LEEM application, respectively. In the near future, further experiments are prepared by using the third gun.

1. Introduction

In order to produce a high brightness beam with a high electron spin polarization (ESP), we have developed transmission-type polarized electron source (PES) [1, 2]. The schematic view of the PES is shown in Fig.1. The PES consists of the transmission photocathode with GaAs-GaAsP superlattice layers and a 20-kV DC-gun with $\mu$m laser focusing system.

In the reference papers [1, 2], we reported the specifications of the prototype PES named "JPES-1". With regard to the photocathode, the GaAs-GaAsP strained strained superlattice was grown on GaP substrate, which is transparent for the laser of around 800 nm wavelength, and an ESP of $90\%$ and quantum efficiency (QE) of $0.09\%$ were achieved simultaneously at 20 kV extracted voltage. Concerning the 20-kV DC-gun, a laser spot diameter of a few $\mu$m was obtained on the photocathode surface and the brightness of $2 \times 10^7$ A.cm$^{-2}$.sr$^{-1}$ was achieved. These performances are almost equal in ESP and better in brightness by three orders of magnitude, compared with those achieved by the no-transmission PES [3, 4].

Encouraged by these results, another two electron gun named "JPES-2" and "JPES-3" was manufactured by the same mechanical designs as that of JPES-1. JPES-1 has been used for the
Figure 1. Schematic view of the Transmission PES

photocathode R&D at Nagoya University. JPES-2 had been already installed in the Low Energy Electron Microscope (LEEM) apparatus operated at Osaka Electro-Communication University (OECU). In the Spin-LEEM experiments at OECU, we had demonstrated a dynamic observation of magnetic images during the growth of Co on W(110) with an acquisition time of 0.02 s with a field view of 6 μm [5]. The acquisition time of a magnetic image by the conventional Spin-LEEM is between fractions of seconds and several tens seconds, which depends on the degree of the magnetic contrast, and the acquisition time of 0.2 s/frame without switching of spin direction has been performed [6]. Furthermore, several experiments by using JPES-3 are also scheduled now and the details will be described elsewhere.

In this paper, we reviewed the recent results of the photocathode R&D and the operation status of electron guns.

2. Transmission Photocathode
The transmission photocathodes were fabricated by using a low-pressure organometallic vapor phase epitaxy (OMVPE) system with a vertical cold-wall quartz reactor at Nagoya University. A commercially available GaP wafer with a Zn dopant of $1.4 \times 10^{17}$ cm$^{-3}$ was used as a transmission substrate. To control the strain property in the buffer and SL layers [2, 7], the GaAs inter-layer was grown on the GaP substrate. Then, 1 μm of the GaAsP buffer layer and 12 pairs of SL layers were grown with a Zn dopant concentration of $1.5 \times 10^{18}$ cm$^{-3}$.

By using this photocathode and JPES-1, an ESP of 90 % and QE of 0.09 % was achieved simultaneously at 20 kV extracted voltage. The performances are almost equal in ESP but a bit lower in QE, compared with those achieved by the conventional photocathode [3, 4]. However, we believe that the polarization improved as a result of the control over strain relaxation in the buffer layer. Because the absorption of the laser power by the GaAs inter-layer was estimated about 50 % and we observed many crosshatches in an atomic force microscope image, which indicates the relaxation of tensile strain in the GaAsP layer [8]. We are doing the improvement designs of the photocathode and QE measurements now.

3. 20-kV electron gun
3.1. Electrode design and dark current measurement
Three electron guns were developed at Nagoya University and the accelerating electrodes were designed by using the own simulation code [9] of N.Y.. At first of JPES-1 experiments, a pair of titanium electrodes was installed at Gun chamber and the accelerating voltage and the electrode gap were set to be 20 kV and 5 mm respectively. In the experiment of these electrodes, dark
currents of a few nA were observed at 20 kV. Since the electrode made of a molybdenum cathode and titanium anode was found to suppress dark currents by our previous study [10], we replaced the titanium cathode to the molybdenum one and the electrode gap were also changed to be 4 mm. As a result, dark currents were successfully suppressed to at most 1 nA at 20 kV and a few nA at 30 kV. Details of these experiments will be reported in another paper.

3.2. Beam brightness measurement
For the purpose to calculate the beam brightness, the beam profile was measured using the knife-edge method at 53.1 cm downstream from the photocathode. The angular current density \( \frac{dI}{d\Omega} \) and brightness \( B \) of the electron beam are calculated by the following equations[1],

\[
\frac{dI}{d\Omega} = \frac{I \cdot L^2}{\pi (S_L - S_o)^2}, \quad (1)
\]
\[
B = \frac{1}{\pi \cdot S_o^2} \cdot \frac{dI}{d\Omega}. \quad (2)
\]

Here, \( L \) is the drift length between the source and the above brightness monitor (BM), and \( S_o \) is a virtual source radius at the photocathode surface. \( S_L \) and \( I \) represent the beam radius and current measured by the BM. For \( S_o \), the virtual source size must be employed due to the beam focusing property caused by the electrode design, and it was estimated to be about 70% smaller than the emission area by beam tracking simulations.

The laser spot size could be well measured by a charged coupled device, but the emission area was enlarged due to the diffusion effect inside the photocathode. We assume that the diffusion length in the photocathode is 0.25 \( \mu \)m.

The data was taken under an emission current of 5.3 \( \mu \)A with a laser spot radius of 0.65 \( \mu \)m and an angular current density of 248 mA/sr and a brightness of \( 2.0 \pm 0.8 \times 10^7 \) A.cm\(^{-2}\).sr\(^{-1}\) were obtained. This brightness is better by three orders of magnitude, compared for the conventional PES.

3.3. Vacuum condition and beam lifetime
The NEA surface is known to be easily degraded by the desorption of residual gas molecules and the back bombardment of positive ion produced by the beam itself. Therefore the base pressure near the photocathode was maintained less than 1.0 \( \times \) 10\(^{-9}\) Pa by using an 100 L/s ion pump and a 2000 L/s non-evaporable getter pump.

The QE lifetimes without electron beams were measured at JPES-1. Two series of data for different conditions were shown in Fig. 2. The open circle points (red color) indicate the results with the condition of no laser and extracted voltage of 20 kV, and the open square (blue) with the estimated laser density of 473 W/mm\(^2\) on the photocathode and no extracted voltage. The vacuum pressure at measurements was 1.4 \( \times \) 10\(^{-9}\) Pa and the dark currents between electrodes were less then 1 nA at 20 kV extracted voltage. Both results seems to be constant, demonstrating that there is no observable evidence of the QE degradation due to dark currents and laser heating.

We have also measured beam lifetimes during the experiments of JPES-1. The measurements were carried out with beam current decay mode and the extracted voltage of 20 kV. The lifetime was defined as the period until the QE value decreased to \( 1/e \) of the initial value. The charge density lifetimes as a function of the operation pressure are shown in Fig. 3 and three typical data of the Fig. 3 was summarized in Tab. 1. The charge density lifetimes increase as the operation pressures decrease and a maximum value of \( 1.8 \times 10^8 \) C.cm\(^{-2}\) was achieved. The data was obtained with the initial current of 3 \( \mu \)A and the laser radius of 3.2 \( \mu \)m, corresponding to the beam lifetime of 36 hours and the charge lifetime of 260 mC (See Tab. 1). Especially the
Figure 2. Dark lifetime with two different conditions

Figure 3. Charge density lifetime as a function of operation pressure

operation pressure during SPLEEM experiments, which needs the beam currents of around 1 μA, were less than $1 \times 10^{-9}$. Then reactivation of a photocathode surface is not necessary for two or three months.
### Table 1. Typical data of beam lifetime measurements

| Initial Current (μA) | Current Density (mA/mm²) | 1/e lifetime (hour) | Total charge (mC) | Charge Density (C/cm²) |
|----------------------|--------------------------|---------------------|-------------------|------------------------|
| 3                    | 82                       | 36                  | 260               | $1.8 \times 10^8$      |
| 2                    | 55                       | 50                  | 213               | $1.5 \times 10^8$      |
| 1                    | 27                       | 55                  | 126               | $8.8 \times 10^7$      |

#### 4. Summary

The high brightness PESs were developed by using transmission-type photocathodes with GaAs-GaAsP strained superlattice layers and electron guns with μm laser focusing system. The developments were successfully done and a brightness of $2.0 \pm 0.8 \times 10^7$ A cm⁻² sr⁻¹ and an ESP of 90% were simultaneously achieved at 20 kV beams. Furthermore, very highly charge density lifetime are obtained with the extreme high vacuum conditions. Up to now, three electron guns are manufactured at Nagoya University, and those are used for photocathode R&Ds and applications of polarized electron beam.

At present except for the QE value, the performances of transmission photocathodes are higher compared with conventional photocathodes and the photocathodes could be applied not only for material science but also high energy accelerators, such as a linear collider and an energy recovery linac. To demonstrate promising advantages of transmission photocathode for these applications, further experiments are required. Then we are prepared for the generation of the multi-bunch beam and the emittance measurement in near future.

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#### References

[1] Yamamoto N, Nakanishi T, Mano A, Nakagawa Y, Okumi S, Yamamoto M, Konomi T, Jin X, Ujihara T, Takeda Y, Oshima T, Saka T, Kato T, Horinaka H, Yasue T, Koshikawa T and Kuwahara M 2008 *Journal of Applied Physics* **103** 064905

[2] Jin X, Yamamoto N, Nakagawa Y, Mano A, Kato T, Tanioku M, Ujihara T, Takeda Y, Okumi S, Yamamoto M, Nakanishi T, Saka T, Horinaka H, Kato T, Yasue T and Koshikawa T 2008 *Applied Physics Express* **1** 045002

[3] Nakanishi T, Togawa K, Baba T, Furuta F, Horinaka H, Kato T, Kurihara Y, Matsumoto H, Matsuyama T, Nishitani T, Okumi S, Omori T, Saka T, Suzuki C, Takeuchi Y, Wada K, Wada K, Yamamoto M and Yoshioka M 2000 *Nuclear Inst. and Methods in Physics Research, A* **455** 109

[4] Nishitani T, Nakanishi T, Yamamoto M, Okumi S, Furuta F, Miyamoto M, Kuwahara M, Yamamoto N, Naniwa K, Watanabe O, Takeda Y, Kobayakawa H, Takashima Y, Horinaka H, Matsuyama T, Togawa K, Saka T, Tawada M, Omori T, Kurihara Y, Yoshioka M, Kato T and Baba T 2005 *Journal of Applied Physics* **97** 049007–049007

[5] Suzuki M, Hashimoto M, Yasue T, Koshikawa T, Nakagawa Y, Konomi T, Mano A, Yamamoto N, Kuwahara M, Yamamoto M *et al.* 2010 *Applied Physics Express* **3** 026601

[6] Ramchal R, Schmid A K, Farle M and Poppa H 2003 *Phys. Rev. B* **68** 054418

[7] Jin X, Maeda Y, Saka T, Tanioku M, Fuchi S, Ujihara T, Takeda Y, Yamamoto N, Nakagawa Y, Mano A, Okumi S, Yamamoto M, Nakanishi T, Horinaka H, Kato T, Yasue T and Koshikawa T 2008 *Journal of Crystal Growth* **310** 5039 – 5043 ISSN 0022-0248 the Fourteenth International conference on Metalorganic Vapor Phase Epitax, The 14th International conference on Metalorganic Vapor Phase Epitax

[8] Jin X, Maeda Y, Sasaki T, Arai S, Ishida Y, Kanda M, Fuchi S, Ujihara T, Saka T and Takeda Y 2010 *Journal of Applied Physics* **108** 094509 (pages 6)
[9] Yamamoto N, Mizuno A, Masuda K, Kan K, Matsumoto S and Yamamoto M 2009 AIP Conference Proceeding vol 1149 ed Crabb D G, Prok Y, Poelker M, Liuti S, Day D B and Zheng X (AIP) pp 1174–1178

[10] Furuta F, Nakanishi T, Okumi S, Gotou T, Yamamoto M, Miyamoto M, Kuwahara M, Yamamoto N, Naniwa K, Yasui K, Matsumoto H, Yoshioka M and Togawa K 2005 Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 538 33–44