TIME RESPONSE MEASUREMENTS FOR TRANSMISSION-TYPE GAAS/GAASP SUPERLATTICE PHOTOCATHODES *

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Abstract

Transmission-type polarized photocathodes could be simultaneously realized high electron spin polarization of around 90 % and high brightness of 2×10^7 A/cm^2/sr. In order to characterize temporal performances of these type photocathode in picosecond ranges, a measurement system was designed and constructed. A TM012-mode 2.6 GHz deflection cavity was used for this purpose and a measurement resolution of 2.8 ps was achieved. As a result of the measurement for a transmission-type GaAs/GaAsP strained superlattice sample, a pulse length contained 90 % of the total charge, fast and slow decay constants were evaluated to be 14.0 ± 0.2, 5.24 ± 0.04 and 9.30 ± 0.13 ps, respectively.

INTRODUCTION

Transmission GaAs-type semiconductor photocathodes (T-PCs) have the great advantages for an achievable beam brightness and an electron spin polarization (ESP). For the beam brightness, we can obtain the diffraction-limited laser spot size when a laser light is injected from the back surface of PCs and the brightness of 2×10^7 A/cm^2/sr was demonstrated [1]. For the ESPs, the improvements with simultaneous high quantum efficiencies (QEs) have been done [2–4]. Up to now, the ESP of 92 % and QE of 1.6 % were simultaneously achieved by using the strain-compensated superlattice (SL) technique [4].

The first demonstration of the novel performance of T-PCs as an electron microscopy source was reported by Osaka-Electro-Communication University group using a low-energy electron Microscope [5]. In that study, a set of T-PCs and 20- kV high brightness gun [1] was applied, and they achieved to obtain magnetic images with an acquisition time of 0.02 s with a field of view of 6 μm and demonstrated a dynamic observation of magnetic images during the growth of Co on W(110) with an acquisition time of 0.2 s with a field of view of 6 μm. After them, T-PCs have been applied to various measurement systems. One of the attractive application of T-PCs is the pulsed transmission electron microscopy (TEM) which is being developed at Nagoya University [6].

For the time resolved application such as a pulsed-TEM, the identification of the temporal performance is important and that for conventional GaAs-type PCs have been studied and reported in picosecond ranges by several groups [7–10], but any measurement result with T-PCs has not been reported. The typical difference with the conventional and transmission-type PCs are in substrate materials, which for the conventional PCs is a GaAs and for T-PCs is GaP. In practical, the polarized electron is generated in SL layers near the surface-side. Then the significant difference for the temporal performance with those PCs was considered to be small. However, the identification of the temporal response for T-PCs has a point not only for practical applications but also for the understanding of electron diffusion and ESP-degradation process in the semiconductor. In this motivation, a temporal response measurement system specially designed for T-PCs was developed [11] and the precisely measurements have been carried out.

In order to study the temporal response directly and precisely, a measurement system with an radio-frequency (rf) deflection cavity was designed and constructed. The temporal resolution of the observed electron distribution was 2.8 ps and the electron bunch length contained 90 % charge of 14.0 ± 0.2 was evaluated. In this paper, the detail of a PC sample and apparatus of our experiment are described in Secs. II and III, and the experimental results are given in Sec. IV.

PHOTOCATHODE SAMPLE

A transmission-type GaAs/GaAsP strained-SL PC was used for the temporal response measurements. The PC design was based on Fig. (a) of Ref. [2], but the Si_3N_4 anti-reflection coating was not existed for the sample PC. The structure was grown on a Zn-doped (001) GaP substrate (1.34×10^{18} cm^{-3}) using a low-pressure organometallic vapor phase epitaxy (OMVPE) system with a vertical cold-wall quartz reactor. To fabricate the SL structure, following the growth of a 600 nm $Al_{0.4}Ga_{0.6}As$ inter-layer and a 1 μm $GaAs_{0.67}P_{0.33}$ buffer layer, 12 pairs of 7.3 nm $GaAs/GaAs_{0.67}P_{0.33}$ strained SLs were grown at 660 ^oC with a Zn dopant concentration of 1.5×10^{18} cm^{-3}. Subsequently, the SL structure was coated with a highly doped 5 nm GaAs layer with a Zn dopant of 6×10^{19} cm^{-3}. As a result of rough analysis after fabrication, the maximum ESP of 84 % was obtained at the wavelength of 780 nm and at temporal response measurement condition of the wavelength of 800 nm the ESP was 77%.

The PC sample was heat cleaned at 420 °C in the activation chamber and the surface was activated by deposition of small amounts of Cs and O_2. The QE in the reflection-PC mode was monitored by simultaneous measurements of photocurrent and laser irradiation power. Then the sample was transferred from the activation chamber to the gun chamber. It was locked at the center of the cathode electrode

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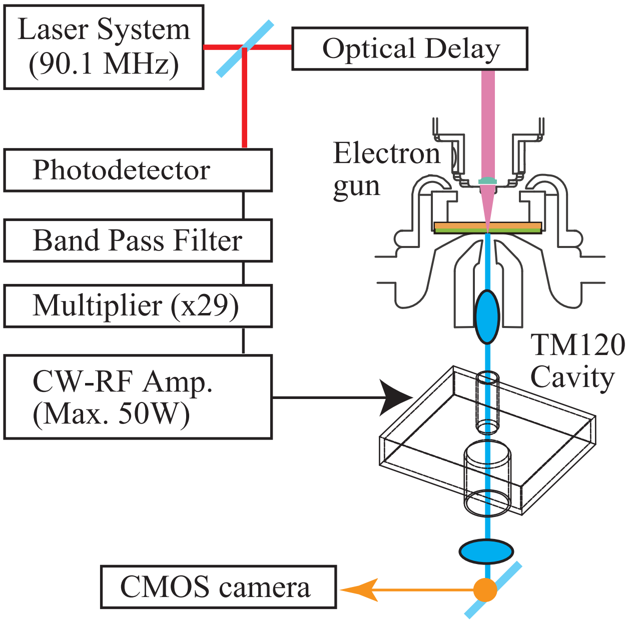

Figure 1: Schematic View of the measurement system and Timing Diagram.

and the QE in operation mode was measured by applying an extraction voltage and irradiating the T-PC from the back. The quantum efficiency of the PC sample was 0.0225 % during temporal response measurement.

EQUIPMENTS

The measurement system consists of a pump laser system, a 20-kV DC electron gun, an rf deflection cavity [11] and an beam profiling system (shown in Fig. 1). An activated PC was installed to the electron gun by a transfer loadlock system. The electron gun equipped with a diffraction-limited laser focusing system [1] and could generate high brightness beams. A mode-locked Ti:Sapphire laser (COHERENT, MIRA) with 90.1 MHz pulse reputation rate was used to illuminate the PC. The laser wavelength and bandwidth were 800 nm and 13 nm with Full Width at Half Maximum, respectively. The laser pulse was synchronized with a 2.6-GHz deflection cavity. By passing through the cavity, the profile of the electron bunch changed from longitudinal to transverse. A screen monitor with a thin fluorescent coating screen was located 0.6 m downstream of the deflection cavity and was recorded with a 8-bit CMOS camera (The imaging source, DMK23GM021). The single pixel size was confirmed by the comparison with the measurement profile using the knife-edge plate and a Faraday-cup charge monitor and corresponded to 22 μm of the screen image. A solenoid magnet located upstream of the deflection cavity was used to adjust the transverse beam size at the screen monitor.

A TM012-mode rf deflection cavity was used to change the electron bunch profile from longitudinal to transverse. A rectangular cavity was designed and made of Oxygen-Free Copper. The resonance frequency is 2612.9 MHz that is 29 times of laser reputations (90.1 MHz). The longitudinal length was chosen to 46.81 mm with consideration for beam deflection efficiency. The fabrication and assembling of the cavity was made at Equipment Development Center of IMS and Mechanical Engineering Center of KEK.

For the manufactured cavity, a set of rf measurements was performed with an Agilent N5230A Network Analyzer. The frequency tuning range was 2.9 MHz from 2611.2 to 2614.1 MHz with six frequency tuners. The loaded and unloaded quality factors were 10,155 and 20,565 respectively and were consistent with the calculation (only just 4% below). The gradient of magnetic field along with longitudinal direction was also measured by the bead-pull method and confirmed with the HFSS simulation. The power is provided by an antenna-type coaxial coupler with an N-type connector. The coupling factor β was 1.02.

In order to synchronize the electron bunch with the rf phase of the deflection cavity, the rf signal around 90.1 MHz was passively generated from a mode-locked laser signal by using a silicon photodetector (EOS, ET-2030A) and a band pass filter. The timing jitter between the PC pump laser and the converted signal by the photodetector was measured by a streak camera (HAMAMATSU, C5675, C5679), and was confirmed to less than 2 ps in root-mean-square (RMS) which was limited by the measurement accuracy of the streak camera. The obtained rf signal was converted to 2612.9 MHz by using a 29-times frequency multiplier (R&K, custom-ordered). Finally, the rf signal passing through a phase shifter to adjust between the beam and rf phases was amplified up to 50 W and was fed to the deflection cavity.

The measurements were done with the input power of 13 W in this paper. The input rf frequency was tuned to the resonant frequency of the cavity by tuning the pump laser reputation rate. A net kick angle was calibrated by measuring beam center positions at the fluorescent screen as a function of the input rf phases and fitting with a sine-function. The kick angle was estimated to be 3.3 mrad for a 20 keV electron. In this condition, 1 pixel of the CMOS image corresponds to 0.36 ps around.

In the experiments, an average beam current was a few nano-ampere and space charge effects are considered negligible at the bunch charge. A typical transverse beam size at profile monitor without any rf power was 137 μm in RMS, which correspond to 2.2 ps in temporal profiles. The exposure time of the CMOS camera was typically several milliseconds. Then the obtained image contained over the fifth powers of ten bunches. The pulse length of the pump laser was estimated around 1 ps, but the measurement accuracy of the laser pulse measurement system, which was used the streak camera described above, was around 2 ps. Then the realistic laser pulse length could not be confirmed and we assumed the worst case for the laser pulse length. In our case, the spatial resolution of the beam profile monitor was enough small, then the temporal resolution of the whole measurement system was determined by the laser pulse length and the transverse beam size, and estimated

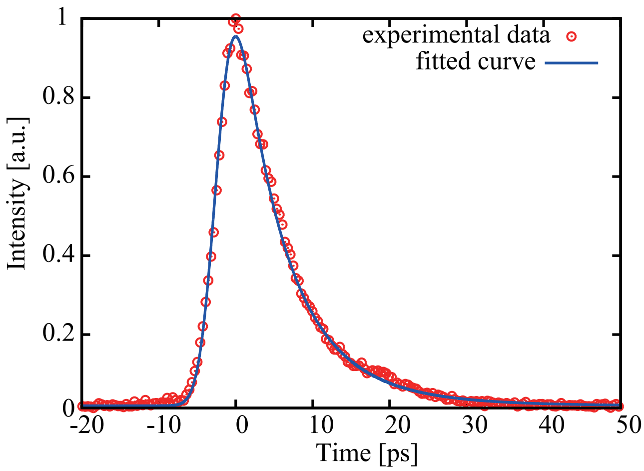

Figure 2: A projection of the bunch trace taken by the beam profile monitor (open circles) and fitted decay curve with an assumed temporal response (solid line).

to be 2.8 ps. It is noted that the accuracy for analytically evaluated parameters would be better than this value.

MEASUREMENTS RESULT

The projected intensities of the bunch trace taken by the beam profile monitor was shown in Fig. 2, where the data points with open circles and a solid line indicate the experimental data and fitted curve with assumed temporal response described below. It is found that the intensity increases exponentially at earlier time around the zero reference time then decays with relative slow time constants. The characteristic time t_{90} and t_{98}, in which 90 and 98 % of the pulse charge are contained, were evaluated to be 14.0 ± 0.2 ps and 27.0 ± 0.2 ps, respectively. There are no distinct discrepancy between our result and that of a conventional GaAs/GaAsP strained-SL PCs reported in Ref. [9]. This result demonstrated that there is no significant differences between electron emission processes for conventional and transmission PCs.

A beam intensity distribution is considered to be shaped by the convolution integral of a normal distribution-like shape come from laser pulse length and transverse beam size, which is characterized by a normal time constant σ_t, and one or more electron retardation mechanisms with the decay constant τ in the semiconductor. Then the convoluted distribution $S(t)$ would be represented by as follows,

$$S(t) \propto \exp\left(\frac{\sigma_t^2}{2\tau^2}\right) exp\left(-\frac{t-t_o}{\tau}\right) \mathrm{erfc}\left(\frac{\sigma_t}{\sqrt{2}\tau} - \frac{t-t_o}{\sqrt{(2)}\sigma_t}\right), \tag{1}$$

where the "erfc" represents a complementary error function. When various retardation mechanisms exist, the distribution function is considered to become the sum of each convoluted distribution.

In the fitting procedure, a pair of decay constants, which are characterised fast and slow decay constants and denoted by τ_f and τ_s, was sufficient to reproduce the experimental distribution. The fitting parameters τ_f, τ_s and σ_t in Eq. 1 were decided to 5.24 ± 0.04 ps, 9.30 ± 0.13 ps and 1.80 ± 0.01 ps, respectively. For the decay constants, 3.30 and 14.8 ps for fast and slow constants were reported for conventional strained SL PCs [9]. The differences might be made as a result of differences of SL structures, crystal qualities, surface work functions (quantum efficiencies) and so on, and more systematic researches are needed for detailed discussions.

CONCLUSION

The measurement system for the T-PC's temporal response was developed and that of a GaAs/GaAsP strained-SL sample grown on a GaP substrate and a AlGaAs interlayer was studied. The measurement accuracy was less than 2.8 ps and was dominated to the timing jitter between with the laser reputation and the rf signal and the focused beam size without rf kicks. The pulse length contained 90 and 98 % of the charge were 14.0 ± 0.2 ps and 27.0 ± 0.2 ps, and a pair of decay constants of 5.24 ± 0.04 and 9.30 ± 0.13 ps was evaluated. The temporal precision determined up to these characteristic values would be expected for various applications using our developed T-PC samples as an electron source.

Furthermore, some discrepancies for retarded decay constants were observed between conventional and transmission PCs. There are some considerable dynamics to understand these discrepancies but we would not discuss in this paper. Further systematic and precisely studies are scheduled in near furthers.

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