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Picosecond electron bunches from GaAs/GaAsP strained superlattice photocathode

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ABSTRACT

GaAs/GaAsP strained superlattices are excellent candidates for use as spin-polarized electron sources. In the present study, picosecond electron bunches were successfully generated from such a superlattice photocathode. However, electron transport in the superlattice was much slower than in bulk GaAs. Transmission electron microscopy observations revealed that a small amount of variations in the uniformity of the layers was present in the superlattice. These variations lead to fluctuations in the superlattice mini-band structure and can affect electron transport. Thus, it is expected that if the periodicity of the superlattice can be improved, much faster electron bunches can be produced.

1. Introduction

Highly spin-polarized electron sources using GaAs-based semiconductor photocathodes have been developed mainly for accelerators in the fields of nuclear and particle physics [1]. Recently, such photocathodes have also attracted considerable attention as electron sources for electron microscopy applications such as low-energy electron microscopy (LEEM) and transmission electron microscopy (TEM), in order to carry out magnetization-sensitive imaging [2–4]. For such applications, high spin polarization is required in order to achieve sufficient image contrast, and high brightness is necessary for fast image acquisition. To investigate changes in magnetic domains with a high temporal resolution, a picosecond time-resolved spin-polarized electron beam is also required [5].

Spin-polarized electron beams are conventionally generated using a GaAs-based photocathode. This type of polarized electron source is based on two fundamental processes: (1) excitation of spin-polarized electrons by a circularly polarized laser beam and (2) electron emission from a negative electron affinity (NEA) surface. The spin orientations of electrons excited by circularly polarized photons from heavy-hole and light-hole bands are opposite to each other. Therefore, high spin polarization is achieved by breaking the degeneracy between the heavy-hole and light-hole valence bands at the Γ point and by exciting electrons only from one of the bands. The degeneracy can be broken by the use of a strained GaAs layer [6,7], superlattice structures [8], and strained superlattice structures [9–11]. The mechanism for generating a spin-polarized electron beam from a superlattice or strained-superlattice photocathode is shown in Fig. 1.

In our previous study, a maximum spin polarization of over 90% was achieved using a GaAs/GaAsP strained superlattice structure on a GaAs substrate [12]. Recently, we have developed a transmission-type GaAs/GaAsP strained superlattice photocathode, which led to a large improvement in brightness [13,14]. In this system, a pump laser light irradiates the back side of the photocathode and photoexcited electrons are extracted from the surface. The advantage of back-side irradiation is that the laser beam spot size can be considerably reduced by using a short-focal-length lens. In order to realize a transmission-type photocathode, we fabricated a GaAs/GaAsP superlattice on a GaP substrate, which has a band gap of 2.26 eV and is thus transparent to the pump laser beam, whose energy is 1.44–1.77 eV, instead of a GaAs substrate with a band gap of 1.42 eV. Using this new photocathode, the brightness of the electron beam was increased by 1000 times or more, up to ~10^7 A cm^{-2} sr^{-1}, while maintaining a high spin polarization of 90% [13]. We then employed this photocathode in a spin-polarized LEEM system and successfully

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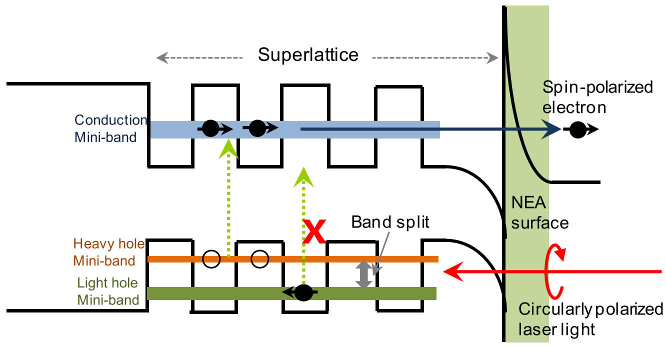

Fig. 1. Mechanism for generating spin-polarized electron beam from superlattice or strained superlattice photocathode.

obtained magnetic images with an acquisition time of 0.02 s [3]. In addition, we are currently developing a TEM system that uses a pulsed spin-polarized electron beam [4].

In the present study, we report the generation of picosecond electron bunches from a GaAs/GaAsP strained superlattice photocathode. The experimental setup and data analysis method are described. We introduce a diffusion model to describe electron transport in the superlattice layers, and the calculated results are found to be in good agreement with experimental observations. Finally, based on TEM observations, the effect of disorder in the superlattice layers on electron transport is discussed.

2. Experimental

Samples were prepared using a low-pressure metalorganic vapor phase epitaxy system with a vertical cold-wall quartz reactor. Triethylgallium, trimethylaluminum, tertiarybutylphosphine, and tertiarybutylarsine were used as source materials. The sample was grown at 660 °C under a reactor pressure of 76 Torr. The photocathode structures used in the present study are shown schematically in Fig. 2. The strained superlattice photocathode shown in Fig. 2(a) was fabricated as follows. After growth of a 2-μm-thick GaAsP buffer layer on a Zn-doped (001) GaAs substrate, 12 pairs of GaAs/GaAsP strained superlattice layers and a 5-nm-thick GaAs cap layer were grown. The P content in the GaAsP buffer layer and the GaAsP barrier layers was 0.33 and the period of the superlattice was 7.2 nm. To compare electron transport in the superlattice to that in bulk GaAs, the photocathode shown in Fig. 2(b) was also prepared. Following growth of a 500-nm-thick AlGaAs buffer layer on a Zn-doped (001) GaAs substrate, a 120-nm-thick GaAs active layer and a 5-nm-thick GaAs cap layer were grown. The Al content in the AlGaAs was 0.4. The AlGaAs layer was used to prevent excited electrons from flowing into the GaAs active layer from the substrate. The Zn dopant concentration in the GaAs/GaAsP superlattice and the GaAs layer was 1.5×10^{18} cm^{-3} and that in the GaAs cap layer was 6×10^{19} cm^{-3}.

The photocathode was installed in a loading chamber and degassed by heating at about 300 °C. It was then transferred to an activation chamber and cleaned by RF heating at a temperature of 540 °C for 1 h. The photocathode surface was activated by repeated cycles of cesium deposition and oxygen supply. The activated photocathode was then installed in a gun chamber.

The experimental setup for the temporal profile measurements is shown in Fig. 3. The temporal response measurements were carried out using a gun voltage of 100 kV. A mode-locked Ti:Sapphire laser with a 81.25-MHz pulse repetition rate was used to illuminate the photocathode. The laser pulses were synchronized using a 2.6-GHz deflection cavity. By passing through the cavity, the profile of the electron bunches changed from longitudinal to transverse. Details of the experimental setup have been previously described by Honda et al. [15].

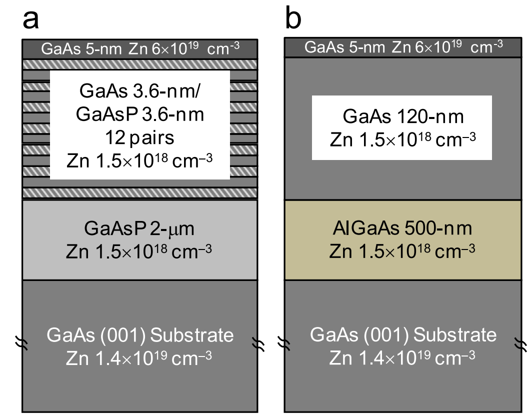

Fig. 2. Schematic diagram of (a) GaAs/GaAsP strained superlattice and (b) bulk GaAs photocathode structures.

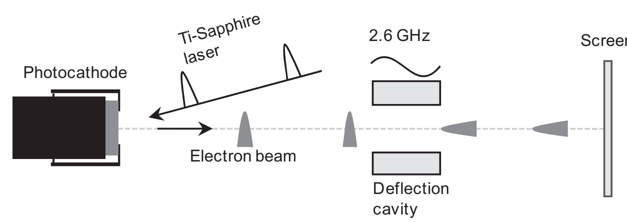

Fig. 3. Schematic drawing of experimental setup for temporal response measurements.

3. Calculation model

Here, we introduce a diffusion model [16] for describing electron transport in the active layer. The temporal change in the electron density can be described by

$$\frac{\partial c(x,\ t)}{\partial t} = D\frac{\partial^2 c(x,\ t)}{\partial x^2} + G(x,\ t) - \frac{c(x,\ t)}{\tau_r}\ , \quad (1)$$

where $c(x,t)$ is the electron density at location x and time t, D is the diffusion constant that characterizes the speed of electron transport, τ_r is the carrier lifetime and $G(x,t)$ is a function describing the electron generation process. The photoexcitation of electrons by a pulsed laser beam with a Gaussian time profile, a pulse duration σ_L and an absorption length α can be expressed as

$$G(x,t) \propto exp\left(-\frac{t^2}{2\sigma_L^2}\right)\exp(-\alpha x) \quad (2)$$

The time dependent emission current I(t) is proportional to the gradient of the electron density at the surface,

$$I(t) \propto \frac{dc(x=0,t)}{dx} \quad (3)$$

The following boundary conditions are applied. On the surface, electrons disappear as they are emitted or trapped in the band bending region, so that

$$c(x=0,t) = 0 \quad (4)$$

At the opposite end of the active layer, there is no electron flow across the buffer layer, so that

$$\frac{dc(x=h,t)}{dx} = 0 \quad (5)$$

where h is the thickness of the active layer.