PRODUCTION OF HIGH INTENSITY POLARIZED ELECTRON BEAM WITH MULTI-BUNCH STRUCTURE

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Abstract

The “surface charge limit (SCL)” phenomenon in negative electron affinity photocathodes with GaAs-AlGaAs superlattice and InGaAs-AlGaAs strained-layer superlattice structures has been investigated systematically. The space-charge-limited electron beam with multi-bunch structure (1.6 A peak current, 12 ns bunch width and 25 ns bunch separation) could be produced from the superlattice photocathodes without suffering the SCL phenomenon. It has been confirmed that the superlattice band structure and heavy p-doping at surface are effective in overcoming the SCL problem.

1 INTRODUCTION

Recently, polarized electron sources based on photoemission from GaAs-type semiconductors with negative electron affinity (NEA) surface have become important tools in several fields of fundamental science. It is also expected that a polarized electron beam will be an essential part of future electron-positron linear colliders. Linear colliders require a high intensity beam with a multi-bunch structure in order to achieve a high luminosity of ~ 10^{34} cm^{-2} s^{-1}. For example, one hundred micro bunches with a bunch separation time of 1.4 or 2.8 ns must be produced at 150 Hz repetition rate for the X or C-band scheme in JLC, respectively. Each bunch is assumed to have more than ~ 2×10^{10} electrons in ~ 700 ps bunch width at the source [1].

The generation of such a closely-spaced multi-bunch beam is not easy due to a so-called “surface charge limit (SCL)” problem. The emission of the conduction band electrons is strongly suppressed when an NEA photocathode is illuminated with a high intensity laser light whose photon energy is close to the band gap energy. The charge saturation level becomes lower than that of the space-charge-limit determined by Langmuir-Child’s law. The SCL phenomenon appears also in multi-bunch beam generation. For example, the charge of the second bunch is much reduced compared to that of the first bunch for the photocathode of the strained GaAs with medium doping [2]. Therefore, development of a new type photocathode which will not suffer from the SCL phenomenon is a very important subject. In this paper, we report on the experimental results using the superlattice photocathodes which give the solutions for the SCL problem [3].

2 SURFACE CHARGE LIMIT PROBLEM AND SUPERLATTICE PHOTOCATHODES

The photoemission process for NEA photocathodes is shown in Fig. 1 [4]. Some of the excited electrons drifting toward the surface can escape to the vacuum and become the extracted beam (J_{escape}). However, the remainder of them ($J_{surface}$) are trapped at the surface band bending region (BBR) and becomes the surface charge (Q_S). These trapped electrons can disappear through another recombination process caused by the tunneling current of holes which penetrate the barrier potential of the BBR and reach the surface (J_{tunnel}). The rate of change of the surface charge is described by

$$\frac{dQ_S}{dt} = J_{surface} - J_{tunnel} \ .$$

If $J_{surface} > J_{tunnel}$, the surface charge is being accumulated and J_{escape} is not proportional to the excited electrons. Therefore, to overcome the SCL problem, the following two conditions must be satisfied simultaneously by the photocathode : (1) high tunneling probability of conduction electrons against the surface potential barrier (low $J_{surface}$) and (2) high tunneling probability of valence holes against the surface band bending barrier (high J_{tunnel}).

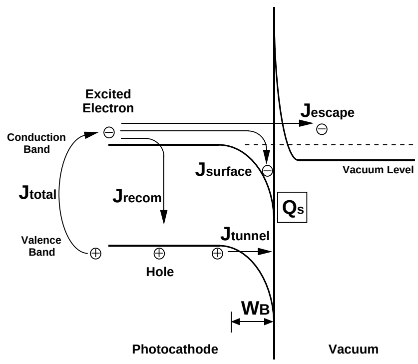

Fig. 1 Photoemission process for an NEA photocathode.

If an NEA magnitude is large enough, the surface charge can be reduced because the current $J_{surface}$ becomes low. We noticed that such a condition can be satisfied by the superlattice photocathode developed by our group [5,6]. The energy level of the conduction mini-band in the superlattice is higher (by ΔE) than the conduction band minimum in the host material of the well layer as shown in Fig. 2. This helps the electrons keep a higher energy at the surface, and thus the escape probability will be higher.

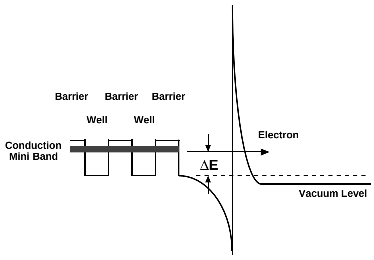

Fig. 2. Energy diagram of a conduction mini-band in an NEA superlattice.

In order to increase the J_{tunnel}, the width of the BBR (W_B) is reduced by increasing the doping density. It is believed that the narrower the W_B, the higher the J_{tunnel} becomes, and this induces a faster recombination of the trapped electrons with holes [2]. The Be-doping density of 4×10^{19} cm^{-3} at the surface is realized for the superlattice by the MBE method.

Up to now, two kinds of GaAs-AlGaAs superlattices (SL-1 and SL-2) and an InGaAs-AlGaAs strained-layer superlattice (SL-3) have been examined for this SCL research. The total thickness of the active layer was chosen to be ~0.1 μm for all samples to reduce the spin-flip depolarization during the emission process. The doping density in the interior of all samples was chosen to be 5×10^{17} cm^{-3}, since higher doping also causes larger depolarization. In order to investigate whether the high surface doping is effective in overcoming the SCL problem for the superlattice, the Be-doping in the BBR of the SL-1 and the SL-3 was chosen to be a high value of 4×10^{19} cm^{-3}, while that of the SL-2 was chosen to be a medium value of 5×10^{18} cm^{-3}. A strain of ~ 1% was brought into the InGaAs well layer of the SL-3. The parameters of these samples are summarized in Table 1.

3 EXPERIMENTAL SETUP

A Nd:YAG-pumped Ti:sapphire laser system is used as the pulsed light source. The full width at half maximum (FWHM) of the laser pulse is 6 – 7 ns and the repetition rate is 10 Hz. The multi-bunch (4 bunches) laser pulse is produced using splitters and delay paths. The bunch separation is tuned to be 25 ns. The time profile of the multi-bunch light train measured by a PIN photodiode is shown in Fig. 3. The full surface of 14 mm diameter photocathode is illuminated with the laser light. For each cathode sample, the pulse laser wavelength is tuned to give the maximum polarization which is measured by a Mott polarimeter.

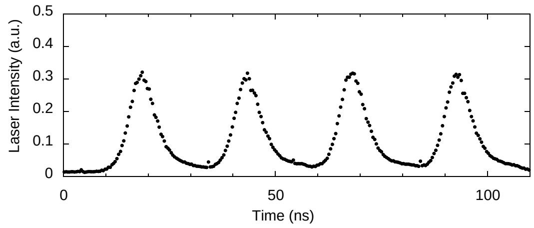

Fig. 3. Time profile of the multi -bunch laser.

The polarized electron gun is operated at −70 kV. The total pressure in the 10^{-11} torr range and the dark current below 10 nA are maintained to achieve long lifetime of the NEA surface. The electron beam trajectories were simulated by using the code EGUN, and a space-charge-limited current of 1.64 A at 70 kV bias voltage and a perveance of 0.0884 μprevs were calculated for our gun geometry. The amount of extracted charge from the photocathode is estimated from the average current measured by a current meter inserted between the cathode electrode and the high voltage cable. The temporal profile of the electron bunch is measured by a Faraday cup.

For polarization measurements, a cw Ti:sapphire laser is used as a light source. A Wien filter is used to rotate the spin polarization vector from the longitudinal to the transverse direction. The polarization is determined by Mott scattering. The maximum polarization and quantum efficiency measured for each superlattice sample are listed in Table 1.

Sample name	x	y	ε (%)	L_W (ML)	L_B (ML)	t (nm)	ΔE (meV)	Surface material	Inside doping(cm^{-3})	Surface doping(cm^{-3})	Pol. (%)	QE (%)	λ (nm)
SL-1	0.0	0.35	0.0	7	11	95	152	GaAs	5×10^{17}	4×10^{19}	69	0.6	748
SL-2	0.0	0.35	0.0	7	25	102	178	GaAs	5×10^{17}	5×10^{18}	67	1.1	739
SL-3	0.15	0.35	1.1	5	11	99	235	InGaAs	5×10^{17}	4×10^{19}	73	0.5	743

Table 1. Parameters of the $In_xGa_{(1-x)}As$-$Al_yGa_{(1-y)}As$ superlattices.

x : fraction of indium, y : fraction of aluminum, ε : strain of InGaAs layer, L_W : thickness of InGaAs (well) layer (ML : mono layer), L_B : thickness of AlGaAs (barrier) layer, t : total thickness of active layer, ΔE : energy difference between the bottom of the conduction mini-band in the superlattice and the conduction band minimum in the host material of the well, Pol. : Maximum electron polarization, QE : quantum efficiency at the maximum polarization, λ : laser wavelength which gives the maximum polarization.

4 RESULTS AND DISCUSSIONS

First, the SL-1 cathode has been tested for multi-bunch generation. The charge saturation curves and the electron bunch shapes taken for different QE states are shown in Fig. 4, where the total charge (laser energy) means the sum of the charge (laser energy) of the four bunches and the QE was monitored using a low intensity He-Ne laser with a 633 nm wavelength. For the high QE states, the following data were obtained. (1) The extracted charge increases slowly with laser energy in the saturated region. (2) The peak of the electron bunch becomes flatter and the FWHM becomes wider. The saturated current of ~1.6 A is same as the estimated value by EGUN simulation. (3) No inter-bunch effect is observed. These results show that the electron bunch behavior for the SL-1 is governed only by the space-charge-limit, that is, the surface charge accumulated in the SL-1 is negligible under these experimental condition. Even for the low QE states, the SCL phenomenon is not observed for the SL-1 : the amount of emitted charge is linearly proportional to the laser energy and all of the four bunches keep the symmetrical shapes. This means that the mechanism which determines the QE value is not the same as that which governs the SCL phenomenon. In other words, the low QE photocathode has no direct relation to the severeness of the SCL problem. This fact is easily understood if we assume that the hole tunneling effect is working so well that it cancels the insufficient tunneling effect of conduction electrons to vacuum.

Next, the SL-2 cathode has been examined to clarify the important role of the high surface doping. The results are shown in Fig. 5. For the high QE states, there seems to be no significant suppression of extracted charge due to the SCL phenomenon in the same way as the SL-1. However, such suppression can be seen clearly for the low QE states, and the inter-bunch effect is observed in the temporal profile of four electron bunches. From the comparison of SL-1 and SL-2, it is confirmed that the high surface doping is indispensable to cancel out the SCL phenomenon.

Finally, we report on the SCL result for the SL-3 having an InGaAs-AlGaAs strained layer superlattice structure and a maximum polarization of 73%. There occurs no SCL behavior for the SL-3, similar to the SL-1. The result shows that the effects of superlattice band structure and high surface doping are available not only for a GaAs-AlGaAs superlattice but also for an InGaAs-AlGaAs strained-layer superlattice. We believe that the better polarization performance can be obtained from this InGaAs-AlGaAs strained-layer superlattice by further optimizing the structure parameters while keeping the good SCL performance.

5 CONCLUSION

The systematic study of SCL phenomenon was performed using three kinds of superlattice photocathodes. A space-charge-limited electron beam with multi-bunch structure (1.6 A peak current, 12 ns bunch width and 25 ns bunch separation) could be generated using a GaAs-AlGaAs superlattice with high surface doping. The similar result was obtained using an InGaAs-AlGaAs strained-layer superlattice with high surface doping. We consider a superlattice with a heavily p-doped surface is the best photocathode which can produce the multi-bunch electron beam required for the next generation of linear colliders. In order to demonstrate this conjecture, we are starting to prepare for the next experiments to produce a high intensity multi-bunch beam with 0.7 ns bunch width and 2.8 ns bunch separation.

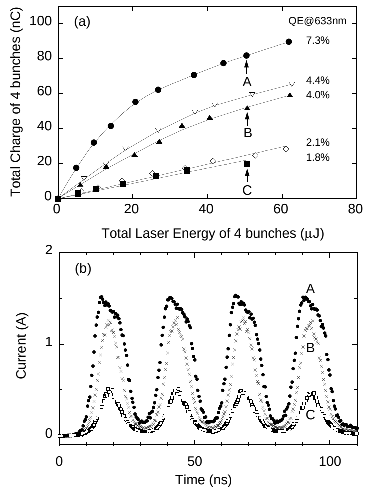

Fig. 4. Charge saturation behaviors taken for different QE states for a GaAs-AlGaAs superlattice with a high surface doping of 4×10^{19} cm^{-3} (SL-1 sample).

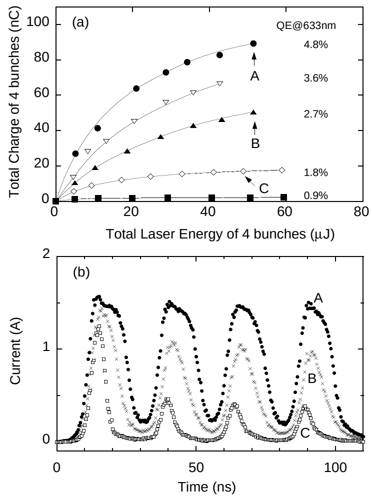

Fig. 5. Charge saturation behaviors taken for different QE states for a GaAs-AlGaAs superlattice with a medium surface doping of 5×10^{18} cm^{-3} (SL-2 sample).

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