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Strained GaAs photocathode for highly polarized electron source

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Abstract

We made a systematic study on the strain GaAs photocathode which was grown on a GaAsP buffer substrate by a MOCVD apparatus. Eight samples with various thickness and lattice mismatches were examined. The strain in each GaAs layer was measured by X ray diffractometry and it was revealed that the strain relaxation occurred partially even in the layer having over tens of Matthews' critical thickness. A clear dependence of electron polarization on the strain was also observed in the region of strain less than 0.5% which corresponds to the energy splitting between heavy-hole and light-hole less than 30 meV. The maximum polarization of $\sim 87\%$ with the quantum efficiency of $\sim 2 \times 10^{-4}$ was obtained by the highly strained $0.085\mu m$ thick sample. The better quantum efficiency of $\sim 1 \times 10^{-3}$ was obtained with the polarization of $\sim 80\%$ by another $0.14\mu m$ thick sample.

1. Motivation

The maximum polarization obtained by the standard GaAs photocathode is limited theoretically to 50%, owing to the degeneracy between heavy-hole and light-hole band at Γ point. It had been a challenging problem to overcome this limitation and three candidates; chalcopyrites, superlattice and strained semiconductors had been studied in the last decade by several groups. We also engaged in such a work for recent several years [1] and in the spring of 1991, we could break the limitation by the first successful strained GaAs photocathode grown on a GaAsP buffer substrate, which had a 86% polarization [2]. At the nearly same time, we could also break the limitation by AlGaAs-GaAs superlattice which had a 71% polarization by a collaboration with KEK and NEC groups [3].

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In order to introduce the strain into the GaAs layer, the interface stress which is caused by lattice-mismatch of a heterojunction was employed. Our motivation to develop this method came from an experiment made in 1987 by H. Horinaka et al. who observed the enhancement of circular polarization of photoluminescence from an InP epilayer grown on an InGaAsP substrate [4].

Following the above breakthrough experiment by strained GaAs layer, we continued a systematic study to optimize the parameters of this photocathode to get not only the higher polarization but also the better quantum efficiency.

2. Choice of the Material for Strained Semiconductor

(a) Conditions for choice of a surface layer

The material of surface layer must be suitable for NEA activation. It must be a direct semiconductor to get high quantum efficiency. The binary compound seems to be better than ternary or quaternary compounds to minimize the depolarization inside the strained layer. As a consequent, GaAs is chosen as a surface layer in this experiment.

(b) Conditions for choice of a buffer substrate

An energy band gap of a buffer substrate must be larger than that of a surface layer in order to avoid the contamination of electrons from the buffer substrate, which has the polarization less than 50%. An adequate amount of difference between two lattice constants of the GaAs surface layer and the buffer substrate is required for inducing the enough strain.

Consequently GaAsP and GaInP are considered as potential candidates. The tensile strain perpendicular to the interface is induced to the GaAs layer by the $GaAs_{(1-x)}P_x$ buffer substrate, while both of tensile and compressive strains are possibly induced by the $Ga_xIn_{(1-x)}P$ buffer substrate. Here, we report on the results obtained from a strained GaAs layer grown on the GaAsP buffer substrate, although a preliminary result from that grown on the $Ga_xIn_{(1-x)}P$ substrate was also already obtained. [5]

3. Experiments and results

We made eight samples whose structures are shown in Table 1. [6]

Zn−doped GaAs	t =800−3100A
Zn−doped $GaAs_{1-x}P_x$	t =1.9−2.3 μm x =0.04−0.33
Zn−doped GaAs substrate (001)	t =350 μm

Table 1. Structure of strained GaAs samples

The polarization, the quantum efficiency and the residual strain which were measured at room temperature are summarized in Table 2. [6] Thickness of GaAs surface layer (t) and a fraction of phosphorous (x) were changed as variable parameters.

Specimen	t(Å)	x	ε_C	ε_R	δ (meV)	t_c (Å)	ESP(%)
1	800	0.04	1.5×10^{-3}	$(1.2\pm0.2)\times10^{-3}$	8	968	40
2	850	0.17	6.1×10^{-3}	$(5.3\pm0.2)\times10^{-3}$	34	176	86
3	1400	0.18	6.4×10^{-3}	$(4.7\pm0.2)\times10^{-3}$	31	164	83
4	2200	0.26	9.3×10^{-3}	$(4.5\pm0.8)\times10^{-3}$	29	102	79
5	2000	0.33	11.8×10^{-3}	$(3.7\pm0.6)\times10^{-3}$	24	74	74
6	3100	0.13	4.6×10^{-3}	$(3.4\pm0.3)\times10^{-3}$	22	247	67
7	850	0.27	9.7×10^{-3}	$(8.0\pm0.2)\times10^{-3}$	52	97	87
8	2100	0.20	7.2×10^{-3}	$(4.8\pm0.2)\times10^{-3}$	31	143	80

Table 2. Parameters of samples and the measured maximum polarizations

Concerning the relaxation of strain in the surface layer, we found the strong correlation between $\varepsilon_R/\varepsilon_c$ and t/t_c as shown in Fig. 1. Here, ε_R is a residual strain which was measured by a double crystal X-ray diffractometry and ε_c denotes the lattice-mismatch which was evaluated from a relation of $\varepsilon_c = 0.0357 \times x$. The t denotes a thickness of the GaAs surface layer and the t_c is a critical thickness for coherent growth, which was evaluated by Matthews' formula [7] as $t_c = (0.224/\varepsilon_c)[1 + ln(t_c/4.00)]$.

The data in Fig. 1 shows that t can be chosen much thicker than t_c without suffering from the drastic strain relaxation. For example, more than 80% (50%) of initial strain remains for the layer thickness up to t/t_c=10 (20).

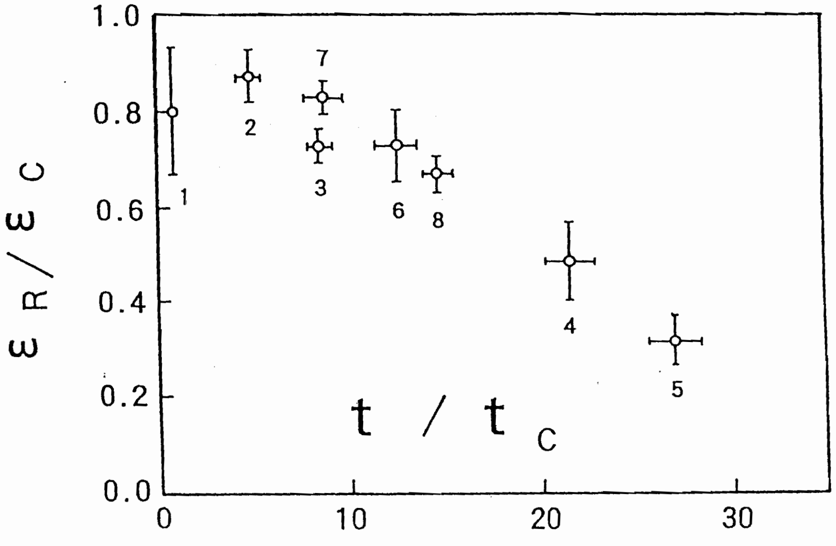

Fig. 1. Strain relaxation in GaAs layers

This fact enables a strained GaAs layer to be feasible as the photocathode of polarized electron source, since it can be expected to extract the reasonable amount of photocurrent. Since ε_c and t_c are functions of x and t, ε_R can be determined for the given set of (x, t) using this correlation curve. It is explicitly shown in the report by T. Saka [8] in this proceedings.

We measured another important dependence of the maximum polarization (P_{max}) on the strain, as shown in Fig. 2. The P_{max} increases as the energy band splitting (δ_s) increases in the region of δ_s less than 30 meV, where δ_s is evaluated as $\delta_s = 6.5 \times \varepsilon_R$ [eV]. Such a strain dependence seems not to be interpreted by the simple theory. An interesting attempt to explain our data by the effect of band mixing between heavy hole and light hole has been made by T. Uenoyama [9].

Anyway, from the practical view point, the data shows that the δ_s must be larger than ~ 30 meV to get the higher polarization than 80%, which corresponds to ε_R of $\sim 5 \times 10^{-3}$.

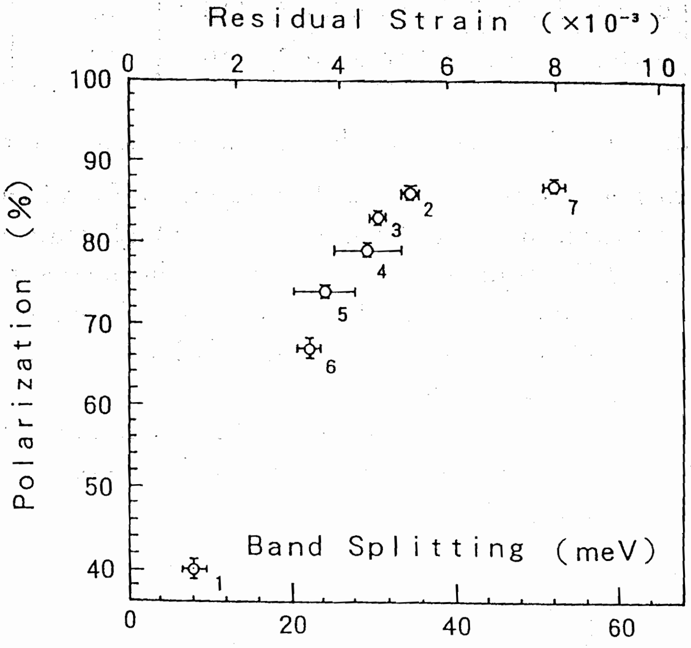

Fig. 2. Strain dependence of the maximum polarization

Linking two experimental results in Fig. 1 and Fig. 2, we can make a rough prediction on the maximum polarization for a cathode having a given set of (x, t).

4. Conclusions

Following properties were confirmed by examining eight samples of strained GaAs photocathodes [6] ;

(1) There is a strong correlation between (residual strain / lattice mismatch) and (GaAs thickness / critical thickness). A large fraction of strain still remains even in the layer which is grown much thicker than the critical thickness for coherent growth.

(2) The strain dependence of the maximum polarization was firstly clarified by our experiment. It indicates the energy splitting between heavy and light holes must be larger than $\sim$ 30 meV to get higher polarization than $\sim$ 80%.

(3) A photocathode performance with the polarization higher than 80% and the quantum efficiency larger than 0.1% was demonstrated to be available for practical use by the present sample.

By this work, a great advance seems to be achieved in developing the high polarization photocathode. [10] However, there still remains an enough space to improve the quantum efficiency by a photocathode with the new structure.

In addition to the photocathode development, construction and performance study of prototype polarized electron guns for high energy accelerator are in progress at Nagoya university and at KEK simultaneously as a part of R/D project of Japan Linear Collider. [11] The first test acceleration of polarized electrons will be done in a couple of years at the Accelerator Test Facility which is under construction at KEK.

5. References

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