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A new type photocathode for the polarized electron source with a distributed Bragg reflector

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Abstract

In order to increase the quantum efficiency of the strained GaAs photocathode for the highly polarized electron source, we designed a new type photocathode with a distributed Bragg reflector (DBR). A Fabry-Perot cavity is formed by the DBR and the GaAs surface. The large enhancement of quantum efficiency was observed at the laser wavelength which satisfied the condition for the resonant absorption of incident laser light. From this experiment, it becomes promising to make the photocathode which has the quantum efficiency more than ~ 1% together with the electron spin polarization higher than 80%.

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1. Introduction

Recently polarized electrons have drawn considerable interests because of their potential applications in particle physics and also in material sciences [1]. At present, GaAs type polarized electron source (GaAs-PES) is the only one which can deliver high intensity beams for practical experiments. As well known, GaAs-PES is based on two fundamental technologies ; laser optical pumping and negative electron affinity (NEA) surface, as shown in fig. 1 [2].

The electron spin polarization (ESP) is attained by the selection rule for absorption of circular polarized photons which excite electrons from the top of the valence band to the conduction band. The maximum polarization obtained by the standard (unstrained) GaAs photocathode is limited theoretically to 50%, owing to the degeneracy between the heavy-hole and the light-hole bands at Γ point.

The NEA technique is indispensable for the electron emission from the conduction band to vacuum. The NEA surface is obtained by a monolayer coverage of alkali metal and oxidant (Cs+O_2 or Cs+NF_3 is usually used) on heavily p-doped GaAs surface in ultra high vacuum.

The performances required for the PES photocathode are high ESP, high quantum efficiency (QE), long life-time and so on. Among them, the high ESP is now available by the strained GaAs [3, 4] and the superlattice [5] photocathodes. Our strained GaAs cathode was made by growing a thin GaAs epilayer on a thick $GaAs_{1-x}P_x$ layer, which results in the tensile strain introduced in GaAs layer by the lattice mismatch. This strain removes the degeneracy and the maximum ESP of $\sim$ 86% was achieved [3]. This type of photocathode has already been employed by the SLC gun at SLAC [6].

However, the QE problem still remains for such high ESP cathodes. For example, the typical QE is $(0.1 \sim 0.3)\%$ with ESP$\simeq$ 80% for the strained GaAs and $(0.1 \sim 0.5)\%$ with ESP$\simeq$ 70% for the superlattice, while the QE of $(1 \sim 10)\%$ is available for the bulk GaAs, although the ESP is low ($\simeq$ 30%). This QE limitation for the strained GaAs cathode comes from two physical reasons ; 1) The electrons are excited only from the heavy-hole band which is the very low density state near the band edge. 2) The thickness of strained GaAs layer is restricted to be less than $0.3\mu m$ to assure the enough strain for the large energy splitting between the heavy-hole and the light-hole bands [7] . These are inherent drawbacks and another new approach seemed necessary to answer to the urgent need for increasing the QE of high polarization photocathodes. Then we pursued the way to develop a new type photocathode with a distributed Bragg reflector (DBR). Here, the first result by this approach is described.

2. Design of a photocathode with a DBR

A cross-sectional view of the new cathode is shown in fig. 2. The cathode structure is quite same as the previous one [7], except that a quarter wave DBR is inserted between the GaAs substrate and the GaAsP layer. The DBR forms a Fabry-Perot cavity with the surface of strained GaAs epilayer whose reflectivity is 32%. The Fabry-Perot cavity of this kind has already been applied to increase the QE of photodetectors by K. Kishino et al. [8]. In their work, it was shown that the absorption of light is enhanced as a result of multiple reflection of light between two parallel mirrors. Guided by their work, the cathode design had been started and the special considerations were made on the following items.

1) The polarity of circular photons : The polarity of circular photons make an essential role to determine the helicity (h) of the extracted electrons. If we use right-handed circular (RHC, h=+1) photons as the incident laser light, right-handed (h=+1) electrons are produced in backward direction and extracted to vacuum, as shown in fig. 1, while left-handed (h= - 1) ones go forward. By the DBR, the RHC photons are reflected and converted to LHC ones [9], as shown schematically in fig 2. Now, these LHC photons produce right-handed electrons in the forward direction, which may be extracted to vacuum. If we use LHC incident photons, the situation is symmetrically changed and left-handed electrons are extracted to vacuum. As a conclusion, the ESP degree is not lost by the reflection of light at the DBR in principle. The same conclusion is obtained for the reflection at the GaAs surface.

2) The DBR design : A DBR is a stack of alternating quarter-wave layers of different refractive indices, which are denoted as n_H and n_L for high and low refractive layers, respectively. If the thickness of each layer is chosen as $\lambda_B/(4n_H)$ and $\lambda_B/(4n_L)$, high reflectivity is expected for the wavelength region around λ_B. The bandwidth ($\Delta\lambda_B$) of the high reflectivity region is given by the formula [10],

$$\Delta\lambda_B = \frac{4\lambda_B}{\pi} sin^{-1}\left(\frac{n_H - n_L}{n_H + n_L}\right)$$

The present DBR is composed of 30 pairs of $Al_{0.1}Ga_{0.9}As$ and $Al_{0.6}Ga_{0.4}As$ layers, where the uppermost one is $Al_{0.1}Ga_{0.9}As$. The refractive index of $Al_xGa_{1-x}As$ is given [11] as

$$n(Al_xGa_{1-x}As) = 3.59 - 0.71\,x + 0.09\,x^2$$

and in our case, $n_H = 3.52$ and $n_L = 3.20$ are obtained. The λ_B is chosen to be 860 nm, because the maximum ESP is expected around this wavelength from our previous data [7]. From those parameters, $\Delta\lambda_B$ is estimated to be ~ 52 nm inside which the DBR reflectivity is assured to be higher than 90%.

3) The resonance condition for a Fabry-Perot cavity : The significant QE enhancement can be expected at the wavelength of λ_R, where the following resonance condition is satisfied.

$$2 \cdot n \cdot L = m \cdot \lambda_R \qquad (m \; : \; integer)$$

Here, n and L denote the refractive index and the total length of the cavity. The wavelength spacing between neighboring resonance is given [12] as,

$$\Delta\lambda_R = \frac{\lambda_R^2}{2 \cdot n_{eff} \cdot L}$$

,where n_{eff} is defined as $n_{eff} = n[1 - (\lambda_R/n)(dn/d\lambda_R)]$

For the present case, $(n_{eff} \cdot L) = [n_{eff}(GaAs) \cdot t + n_{eff}(GaAsP) \cdot l + n_{eff}(DBR) \cdot d]$. Here, t and l denote the thickness of GaAs and GaAsP layers and the design values were $t = 140\,nm$ and $l = 2000\,nm$, respectively. The effective penetrating thickness of light to the DBR is denoted by d and was estimated to be $\sim 700\,nm$ [13]. From the above parameters, $\Delta\lambda_R$ was roughly estimated to be $(20 \sim 30)\,nm$. It means that we can expect two or three resonant peaks in the QE spectrum, because $\Delta\lambda_R$ is smaller than $\Delta\lambda_B$.

More details about the design criteria determined by the simulation for this kind of cathode will be given elsewhere in the near future.

3. Experiments

The DBR, the GaAsP and the GaAs layers were grown successively in a vertical atmospheric-pressure metal-organic vapor phase epitaxial (MOVPE) reactor at Daido Steel Co. Ltd. The sources were trimethylalumiun (TMA), trimethylgallium (TMG), 100% PH_3 and 10% AsH_3 in H_2. The growth temperature was $750°C$ and $800°C$ for growth of the DBR and both of GaAs and GaAsP layers, respectively. The flow rate of TMG+TMA (for DBR) and also TMG (for GaAsP and GaAs) was 10^{-4} mol/min. The design value of the phosphorous fraction in the GaAsP layer was chosen to be $\sim$ 17% which is the same value of a previous cathode with a GaAs layer thickness of 140 nm [7]. However, it turned out that the real value was $\sim$ 12% which was determined by the measurement of the peak wavelength of photoluminescence from the $GaAs_{1-x}P_x$ layer. All layers were grown with Zn doping of $5 \times 10^{18}/cm^3$.

In order to check the optical performance of the device, a reflectivity spectrum was measured by using the monochromatized light with a 3ϕ diameter. The result is given in fig. 3, where a broad band with high reflectivity was clearly observed. The center (λ_B) and the bandwidth ($\Delta\lambda_B$) agreed well with the design values. Three prominent dips at the wavelength of $812\,nm$, $832\,nm$ and $856\,nm$ were also observed, which are expected to be correspondent to the resonance absorption.

The QE and the ESP were measured by a PES apparatus at Nagoya university. It consists of a 4 keV gun and a 100 keV Mott polarization analyzer [14]. The circular polarized photons were supplied by a Ti : Sapphire CW laser with a quarter wave plate.

In fig. 4, the measured QE is plotted by a mark of bullet (•) as a function of the incident laser wavelength (λ). Evidently the periodical QE enhancements were observed in the region of $800nm \leq \lambda \leq 900nm$. The QE of three prominent peaks are 1.8%, 2.5% and 1.3% at laser wavelength of 811 nm, 832 nm and 858 nm, respectively. These QE peak positions agree quite well with the dip positions in the reflectivity spectrum, which are indicated by the downarrows($\downarrow$). This agreement demonstrates clearly that those QE enhancements are owing to the resonance absorption effect.

For evaluation of the device performance, we define the enhancement factor, as a ratio of the QE of the cathode with the DBR to that without the DBR. In fig. 4, the previously measured QE for the cathode [7] with the same thickness of the GaAs and GaAsP layers is also plotted by a mark of circle (o) for comparison. Obviously, the QE's at three peaks are much increased with the enhancement factors of ~ 4, ~ 8 and ~ 10, respectively. It must be remarked, however, that these enhancement values have some ambiguities from two reasons; 1) two surface GaAs layers have slightly different band structures near the band edge due to difference of the phosphorus fractions of $\sim 12\%$ and $\sim 17\%$ in the $GaAs_{1-x}P_x$ layer, and 2) two QE's were measured at the separate times and the QE dependence on the surface conditions may not be negligible.

In fig. 5, the measured ESP is shown with a mark of bullet(•). The other ESP marked by circle(o) denotes the previously measured one. The ESP spectrum of the present cathode shifted slightly to the longer wavelength compared with the previous one. However, this behavior is well understood from the strain difference for two cathodes and it seems to be verified that the multiple reflection of light brings no serious loss of the ESP in this device.

4. Discussions

We tried to fit the QE spectrum by a simulation program in which the transmission matrix method [9, 10] was used for calculating the multiple reflection of light at the BDR and at the surface of GaAs epilayer. The simulated enhancement factor is shown in fig. 4 by a doted line. It is obvious that a gross structure of the QE spectrum was well reproduced by this simulation. From the above experimental data and simulation, it seems plausible that at least the factor five of the QE enhancement may be achieved by this device.

Concerning the application of this method to the other type photocathode, there seems to be many possibilities. For example, it will be effective for the superlattice-PES photocathode. It will be also possibly applied for the RF-gun photocathode [15] in the future.

In the last, one problem must be pointed out for this device. For the PES-photocathode, it is naturally desired that a resonant wavelength (λ_R) coincides with the wavelength (λ_P) where the maximum ESP is obtained. In practice, however, this requirement is not so easy to be satisfied, because the λ_R depends severely on some parameters like the thickness of each layer, the phosphorus fraction of the GaAsP layer and the deviation of λ_R from λ_B. More experimental data and detailed analyses will be given on this point in the forthcoming paper.

In conclusion, the large enhancement of QE for the strained GaAs-PES was achieved by developing the resonant-absorption type photocathode with the DBR. For $0.14\,\mu m$ thickness strained GaAs layer, the QE of $\sim 1\%$ with the ESP of $\sim 70\%$ was observed at the laser wavelength of $\sim 860\,nm$. The usefulness of this approach to increase the QE was demonstrated by this experiment and the applications for other type photocathodes seems to be promising.

Acknowledgment

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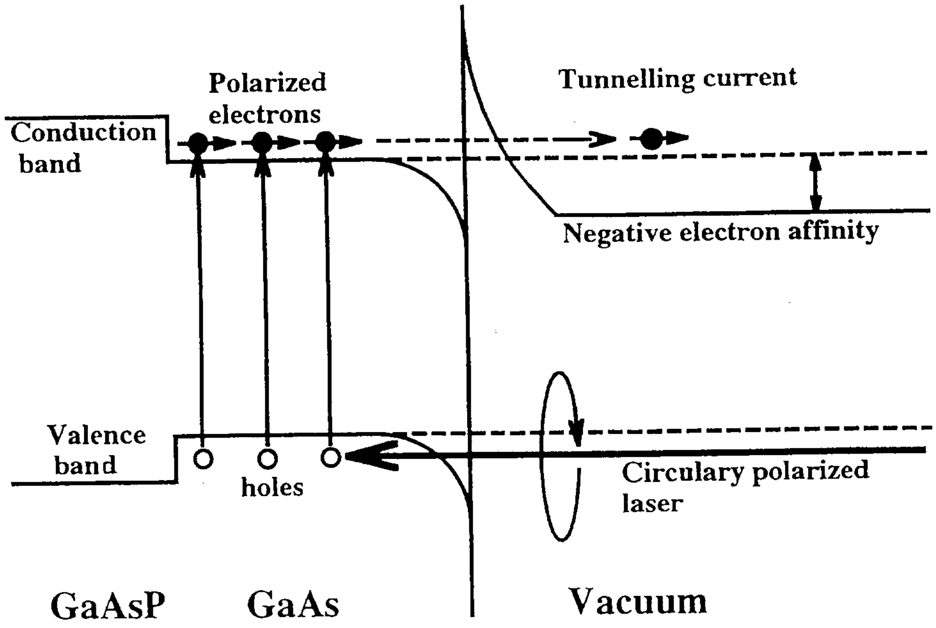

Figure 1. : Principle of strained GaAs polarized electron source. It is based on the optical pumping and the NEA surface techniques.

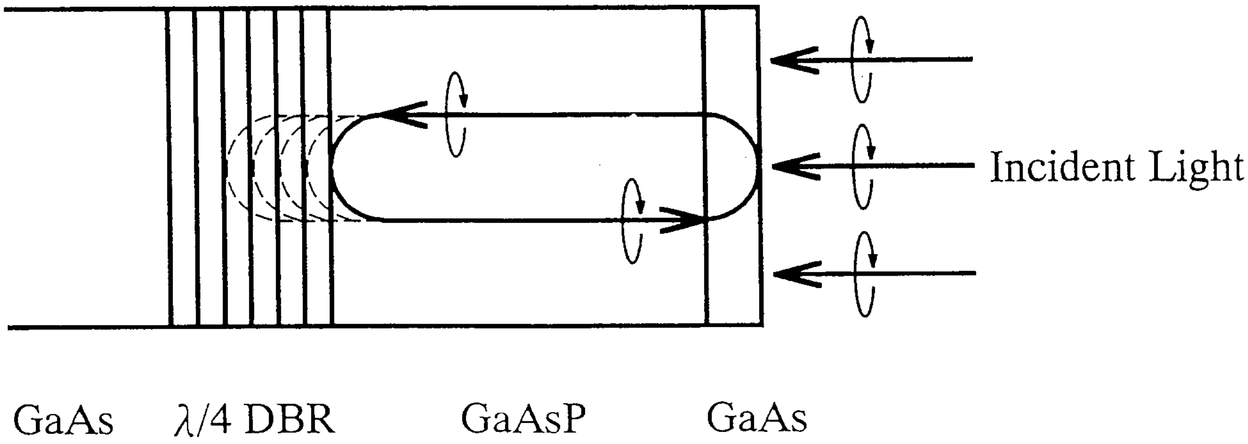

Figure 2. : A schematic drawing of the new type photocathode with the DBR. A Fabry-Perot cavity is formed by the DBR and the GaAs surface. The change of the helicity of photons at two mirrors is also shown.

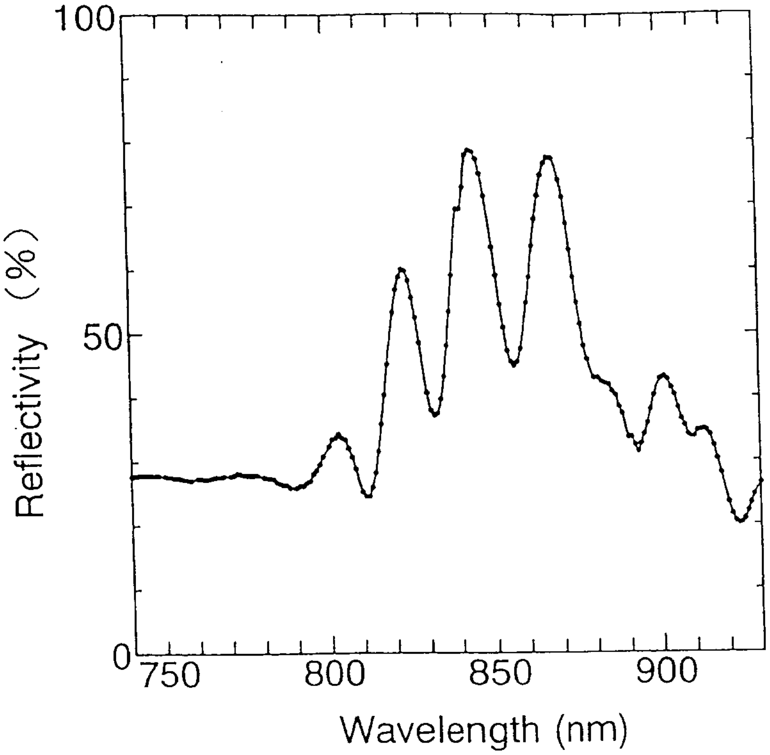

Figure 3. : The reflectivity spectrum. The data was taken by using the monochromatized light with a 3ϕ diameter. Each dip in the high reflectivity bandwidth corresponds to the resonant absorption of the incident light.

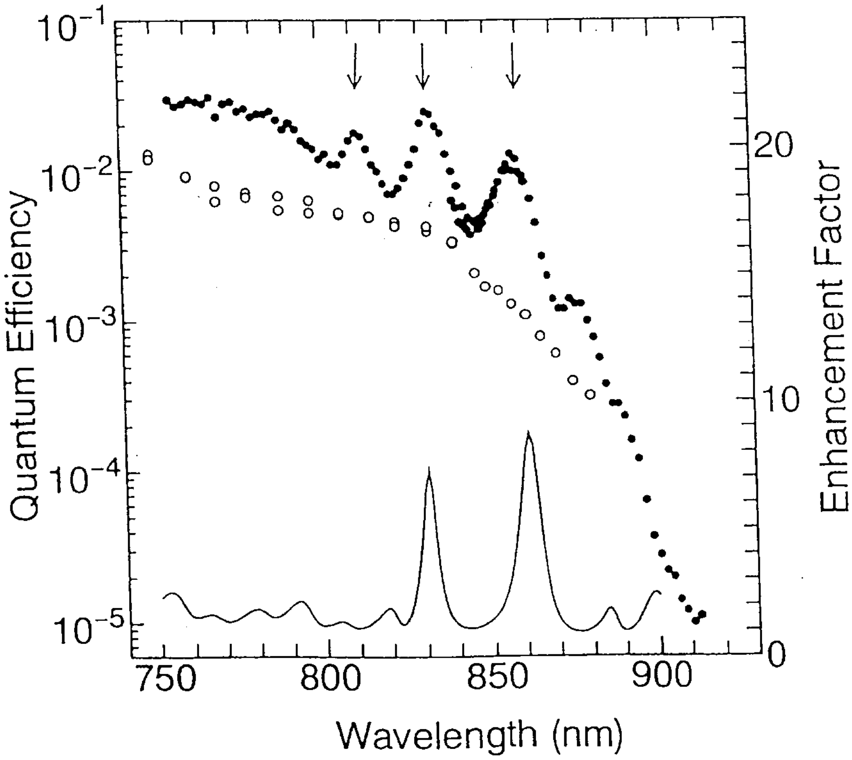

Figure 4. : The quantum efficiency (QE) is plotted as a function of the laser wavelength. The QE of the present cathode is indicated by a bullet mark (•), while that of the previous one without the DBR is marked by a circle (○). The simulated enhancement factor is shown by a dotted line.

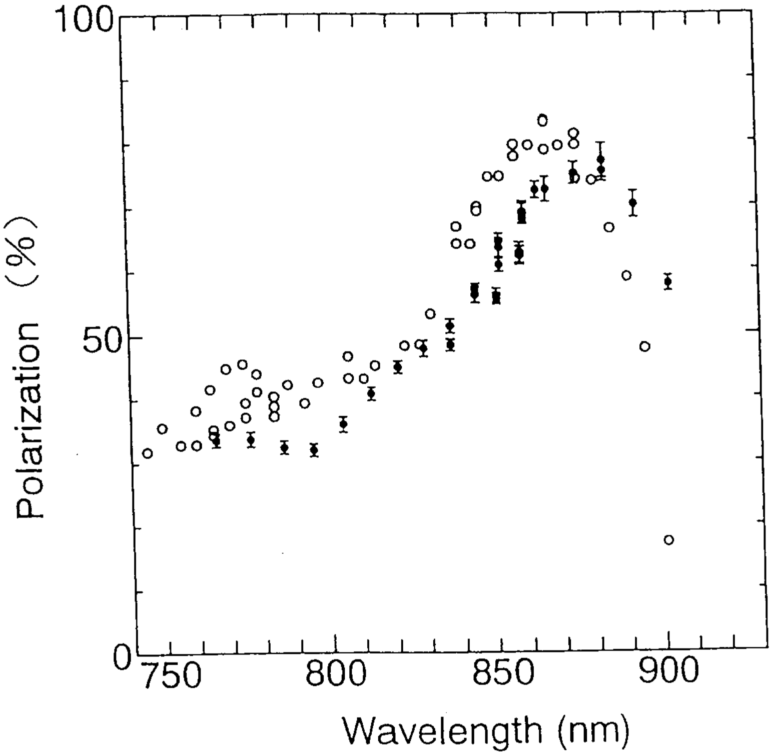

Figure 5. : The electron spin polarization (ESP) is plotted as a function of the laser wavelength. The ESP of the present cathode is indicated by a bullet mark (•), while that of the previous one is marked by a circle (o).