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PHOTOEMISSION FROM III-V SEMICONDUCTOR CATHODES*

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Abstract

Quantum efficiencies (QE) and mean transverse energies (MTE) of GaAs photocathodes grown using various techniques: metal-organic vapor phase epitaxy (MOVPE), molecular beam epitaxy (MBE), and atomic polishing have been compared and found to be identical. GaAs and GaInP based samples grown at Nagoya University were activated and measured in the Cornell ERL photoinjector. These were found to be in agreement with the results obtained at the ERL injector in KEK.

INTRODUCTION

Photocathodes, used as electron sources in photoinjectors, need to satisfy several stringent and often conflicting requirements. An ideal photocathode should have a high quantum efficiency (QE), low mean transverse energy (MTE), quick (<ps) response time and long life-time. For applications requiring high average current the photocathode should have a QE of >1% in the visible range [1]. The maximum achievable beam brightness from photoinjectors is limited by the thermal emittance of the cathode [2]. The thermal emittance ϵ_{th} is related to the MTE and the rms laser spot size σ by $\epsilon_{th} = \sigma\sqrt{\frac{\text{MTE}}{m_e c^2}}$, where $m_e c^2$ is the rest mass energy of the free electron.

III-V semiconductors like GaAs activated to negative electron affinity using Cs and O_2/NF_3 are promising candidates for an ideal photocathode. Although, they are very sensitive to the vacuum conditions, they produce a high QE (>10%) and low MTE (<140 meV) along with a short response time in green light [3]. The process of photoemission from these cathodes can be described by Spicer's 3-step model (of excitation, transport to surface, and emission) using Monte-Carlo based electron transport in the bulk of GaAs [4]. It has also been shown that layered structures of III-V materials with graded doping can be designed and grown to optimize photoemission [5].

To first order MTE is proportional to the excess energy of excited electrons in the conduction band, for a given value of negative affinity. The excess energy of electrons is given by $h\nu - E_g$, where $h\nu$ is the energy of the incident photon and E_g is the band gap of the material. Thus, for a specified wavelength of incident light, a material with higher band gap can give lower MTE. A ternary alloy $Ga_{0.52}In_{0.48}P$ has a band gap of ~ 1.9 eV (0.5 eV larger than GaAs) and is lattice matched with GaAs, making it easy to grow on GaAs substrates. This makes it a good candidate as a possible low MTE cathode.

In this paper, we compare the QE and MTE obtained from commercially available atomically polished GaAs cathodes, GaAs cathodes grown using molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE). QE and MTE of $Ga_{0.52}In_{0.48}P$, grown using MOVPE have also been measured at various wavelengths. Finally, a structure of $Ga_{0.52}In_{0.48}P$ with a 5 nm cap of GaAs was also studied. All the MOVPE samples were grown at Nagoya university, Japan and the MBE samples were grown at Cornell university, USA. The results of MTE agree well with those measured at KEK [6], Japan reinforcing the validity of the measurement.

SAMPLE PREPARATION

Commercial Polished GaAs

Atomically polished GaAs sample p-doped using Zn to a carrier concentration of $0.5 - 2 \times 10^{19}$ cm^{-3} was cleaned with acetone and trichloroethylene (TCE). This sample was then inserted into a activation vacuum chamber with a pressure of less than 5×10^{-11} torr and heated to 620° C for two hours in order to remove all the surface oxides. This procedure produces a clean oxide free GaAs surface with a rms roughness of ~ 10 nm [7].

MBE Grown GaAs

A sample p-doped to a concentration of 5×10^{18} cm^{-3} using Be was grown using MBE on a p-doped substrate at Cornell University. The thickness of the MBE grown layer was greater than 1 um. The sample was then covered with a thick layer of As and transported into the activation vacuum chamber. The As cap prevents the sample surface from oxidizing in air. The As cap was removed in the activation vacuum chamber by heating it only to 350° C. This produces a clean atomically flat surface. The quality of the surface was confirmed using Reflective High Energy Electron Diffraction (RHEED).

MOVPE Grown Samples

Three samples were grown using MOVPE at Nagoya university, Japan and shipped to Cornell University, USA in an evacuated desiccator. They were stored under dry nitrogen for a few months before activation. The samples were mounted on a sample holder in air and inserted into the activation vacuum chamber. They were then heat treated to 550° C for two hours. This treatment does not cause the surface to roughen, but may not remove the oxide completely. The structure of the samples is as follows :

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Table 1: Comparison of QE and MTE measurement at Cornell and KEK. The QE was measured at 532 nm. The MTE was measured at 532 nm in Cornell and at 544 nm in KEK. Both QE and MTE measurements have an error of about 10%

Sample	QE @ Cornell	QE @ KEK	MTE @ Cornell	MTE @KEK
Commercial GaAs	9%	–	117 meV	–
MBE grown GaAs	14%	–	123 meV	–
MOVPE grown GaAs	7%	9%	136 meV	120 meV
MOVPE grown $Ga_{0.52}In_{0.48}P$ with $Ga_{0.52}In_{0.48}P$ cap	3%	11%	126 meV	120 meV
MOVPE grown $Ga_{0.52}In_{0.48}P$ with GaAs cap	10%	14%	145 meV	104 meV

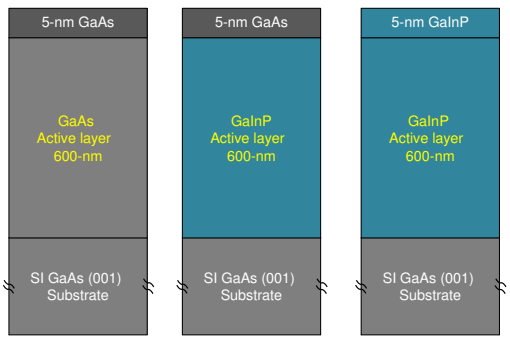

Figure 1: Structure of MOVPE grown samples. For all samples the 5 nm cap layer is p-doped with Zn to a concentration of 6×10^{19} cm^{-3} and the 600 nm active layer is doped to a concentration of 1.5×10^{18} cm^{-3}.

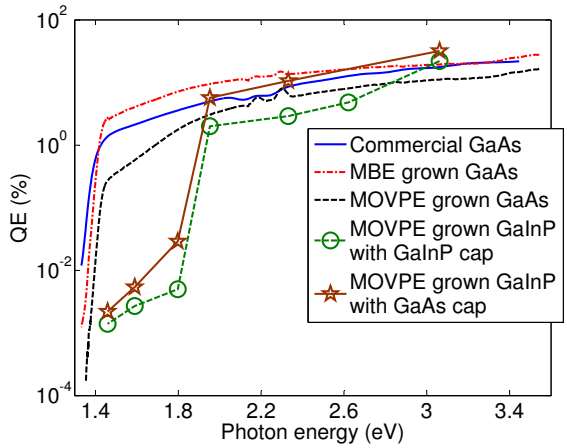

Figure 2: Spectral response of the various samples. The response of the GaAs samples was measured using a monochromator with a Hg vapor lamp, the response of $Ga_{0.52}In_{0.48}P$ samples was measured using several DC lasers

- 5 nm GaAs cap layer over 600 nm GaAs active layer over semi-insulating (SI) GaAs substrate,
- 5 nm $Ga_{0.52}In_{0.48}P$ cap layer over 600 nm $Ga_{0.52}In_{0.48}P$ active layer over SI-GaAs substrate,
- 5 nm GaAs cap layer over 600 nm $Ga_{0.52}In_{0.48}P$ active layer over SI-GaAs substrate.

Figure 1 shows the structure of the MOVPE grown samples.

All the MOVPE grown samples were Zn doped with the dopant concentration of 6×10^{19} cm^{-3} in the cap layer and 1.5×10^{18} cm^{-3} in the active layer. All samples were oriented in the [100] direction.

After cleaning the samples were activated using the yo-yo process. This involves alternating exposures to Cs and NF_3 while measuring the photocurrent under white light illumination [3].

QE AND MTE MEASUREMENT

Spectral Response of QE

The spectral response was measured using a monochromator with a Hg vapor lamp for the GaAs samples. The spectral response of the $Ga_{0.52}In_{0.48}P$ cathodes was measured using several solid state lasers of different wavelengths.

Figure 2 shows the spectral response obtained for all the samples. As expected the spectral response of all GaAs samples shows a sharp drop at the band gap near 1.42 eV. The spectral response of $Ga_{0.52}In_{0.48}P$ show a sharp drop near 1.9eV, which is approximately the band gap of the alloy material. The exact QE strongly depends on the cleanliness of the surface and the vacuum conditions, both of which are difficult to control exactly. Due to the different surface cleaning procedures and the varied doping structures the spectral responses are different for different samples.

Table 1 compares the QE of the samples under illumination of 532nm. QE measurements performed at KEK have also been reported. The differences are mainly due to the sample handling, cleaning and activation procedures followed [8].

MTE Measurement

The activation vacuum chamber is connected to the high voltage DC gun of the Cornell ERL injector. After the spectral response measurement, the MTE was measured in the DC gun using the solenoid scan technique [3]. Figure 3

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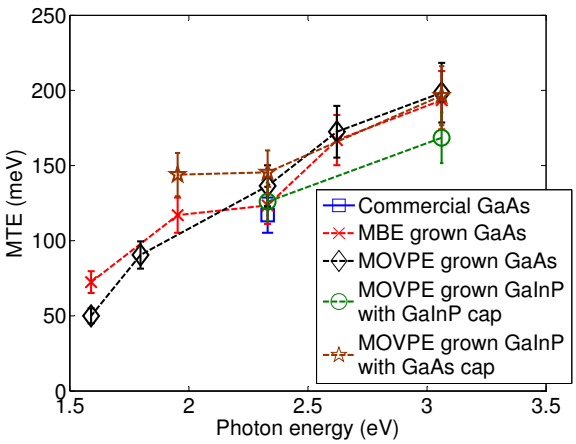

Figure 3: MTE vs incident photon energy. MTE increases as expected with increasing photon energy.

shows the MTE measured at various wavelengths for the different samples.

Table 1 compares the MTE of various samples measured at a wavelength of 532 nm in Cornell university. It also shows the values of MTE measured at 544 nm in KEK [6]. It is important to note that the values presented in [6] are MTE in one of the two transverse directions and hence are half of the values reported here. The values measured at Cornell and KEK are found to be in good agreement.

It can be seen that the various preparation techniques result in very similar MTE values for GaAs. Due to the conservation of transverse momentum during emission and the small effective mass of electrons in the Γ-valley of GaAs, the MTE of a smooth and clean MBE grown GaAs surface is expected to be less than 20 meV [4, 7]. However, the measured MTE is about 120 meV indicating a strong scattering at the surface during emission. The nature of this scattering is not presently understood.

Despite the higher band gap and hence a smaller excess energy of excited electrons, the $Ga_{0.52}In_{0.48}P$ samples have a MTE greater than or equal to the GaAs samples. This could indicate a stronger band bending at the surface, a lower electron affinity, or a stronger surface scattering during emission from this alloy.

CONCLUSION AND DISCUSSION

We observe that even though different surface preparation techniques or varied high p-doping structures result in different QE and spectral responses, they do not have a large impact on the MTE.

The ternary alloy $Ga_{0.52}In_{0.48}P$ even though displays a high QE, it does not provide a small MTE as might have been otherwise expected. The MTE measured from $Ga_{0.52}In_{0.48}P$ is nearly equal to that of the GaAs cathodes at the same wavelengths. This suggest that $Ga_{0.52}In_{0.48}P$ has a stronger band bending, larger NEA or larger scattering at the surface during emission as compared to GaAs. Similar behavior has also been previously observed for the $GaAs_0.55P_0.45$ alloy [3]. A detailed investigation of this phenomenon is necessary.

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