Cooled transmission-mode NEA - photocathode with band-graded active layer for high brightness electron source

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Introduction & Goal

A Free-Electron Laser (FEL) places exacting demands on a Negative Electron Affinity (NEA) photocathode, such as ultra-fast response time, low energy spread for emitted electrons, high Quantum Efficiency (*Q.E.*) and a high average photocurrent. However, these requirements are conflicting, and cannot be fulfilled by conventional photocathode design. For example, to achieve ~10 ps response time, the photocathode active layer should be thinned to ~100 – 150 nm, but this is insufficient to provide near-complete absorption of light with $\hbar\omega \approx E_g$ so high *Q.E.* cannot been achieved. Complete optical absorption and high *Q.E.* can be obtained with a thin active layer at higher photon energies, but this generates photoelectrons with *excess* kinetic energy within the semiconductor. These photoelectrons do not thermalize in a thin active layer, so yield a broad energy distribution in the emitted electrons. Moreover, cooling of the conventional semiconductor structure is ineffective due to its fragility as it cannot be pressed firmly to a heat sink. Consequently, the maximum CW photocurrent is limited to few milliamps. The goal of our work is to develop a new design of NEA – photocathode, which is optimised for FEL applications.

Basic idea & experimental details

Our approach is to design a **transmission-mode GaAs (Cs,O) photocathode with a *composite band-graded* (BG) *active layer* on sapphire substrate.** The energy diagram for this photocathode is shown in fig. 1. During operation, the photocathode is back-illuminated through the sapphire and buffer layer with photons of ~2.3 eV. The BG layer is grown from $Al_xGa_{1-x}As$ with x varied over the range $0<x<0.1$, and absorbs most of the photons. The thickness of the BG layer is ~300 nm and is enough for effective thermalization of photoelectrons within this layer over a period of ~0.1 ps. The variation of the Al content across the BG layer creates a variation in the energy of the conduction band minima, and consequently, creates a 'built-in' electric field whose strength is ~4×10^4 V/cm. It is known from the literature [1] that this electric field accelerates thermalized photoelectrons to the saturation velocity, which is around 10^7 cm/sec. Thus photoelectrons are 'ejected' from the BG layer into the GaAs 'emitting' layer over an estimated time of approximately 3 ps. It then takes ~5 ps for photoelectrons to diffuse across the GaAs layer whose thickness is ~100 nm, then escape into the vacuum [2]. Therefore, the estimated time response of a BG – photocathode does not exceed ~10 ps. To permit a comparative study of photoemission characteristics, a batch of test photocathodes with both BG and homogenous (HM) active layers were manufactured, with fig. 2 showing the BG-photocathodes. The thickness of HM active layer was equal to 130 nm, so slightly exceeds the 100 nm GaAs layer in the BG-photocathode. Both photocathodes were hermetically sealed within test parallel plate photodiodes. The anodes of these photodiodes were made of glass, covered with transparent and conductive In_2O_3 layers. This permitted photoemission to be studied in both transmission- and reflection-mode illumination geometries. Figure 3 shows the test photodiodes. Longitudinal energy distributions for the emitted photoelectrons were measured by applying a retarding potential between photocathode and anode [3]. *Q.E.*s were measured at low electric fields so that the influence of the Shottky effect could be neglected. Experiments were performed at both room and liquid nitrogen (LN_2) temperatures.

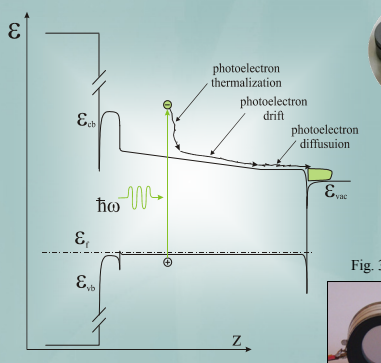

Fig. 1 – BG layer energy diagram

Fig. 2 – Test photocathodes

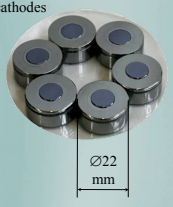

Fig. 3 – Test photodiodes

Results

Q.E. spectra for two photocathodes with both HM and BG active layers, measured in both transmission- (TM) and reflection-mode (RM) illumination geometries are shown in fig. 4. One can clearly see that the *Q.E.*s for both photocathodes are low for photon energies close to the GaAs energy gap and exceed 15 – 20% for $\hbar\omega = 2.32$ eV, when most of exiting photons are absorbed within the active layers. Longitudinal Energy Distribution Curves (LEDC) measured at room temperature in RM illumination geometry for photocathodes with HM and BG active layers are shown in fig. 5 (a), (b), respectively. It is clear that for this illumination geometry, an increase in photon energy is accompanied by an increase in both amplitude and width of the high-energy tail of LEDC. This observation is expected because at 'high' photon energies, the majority of photoelectrons with excess kinetic energy are generated in close proximity to the emitting surface. Consequently, a significant number of non-thermalized electrons are emitted before thermalization, and their contribution to the photocurrent increases in tandem with the increase in photon energy. The BG layer cannot play any role in the RM illumination geometry, however the role of BG layer is changed significantly if the photocathode is illuminated in TM geometry. Firstly, let us consider the photocathode with a HM active layer. If this photocathode is back-illuminated at 'high' photon energy, most photoelectrons with excess kinetic energy are generated near the interface between the active and buffer layers. To be emitted into the vacuum, these photoelectrons must cross the active layer by diffusion. If the thickness of the active layer is approximately 100 nm, the diffusion process takes typically ~5 ps [2]. This time exceeds the photoelectron thermalization time for p-doped GaAs [4], so a large portion of 'hot' photoelectrons generated near the back side of the HM active layer have to be thermalized during their diffusion to the emitting surface. The validity of this statement can be checked through analysis of the data presented on the fig. 6 (a) which shows the LEDC measured for the HM active layer in TM illumination geometry. One can see in fig. 6 that both the amplitude and width of the high-energy tail of the LEDC are approximately two times smaller than those shown in fig. 5 (a) which were measured from the same photocathode in RM illumination geometry. Nevertheless, it is shown that the thickness of the active layer (130 nm) is not sufficient for complete suppression of the 'hot' electron contribution to the photocurrent. Analysis of data presented in fig. 5 (a) has shown that the thickness of the active layer of this photocathode is close to the optical absorption length for $\hbar\omega \approx 2.32$ eV, and to the thermalization length of 'hot' photoelectrons. This is the basis for the remarkable contribution from 'hot' electrons which is detected in the LEDC. To suppress photoemission of 'hot' photoelectrons from a conventional TM photocathode, one has to increase the thickness of HM active layer. However, if this is done, the response time of the photocathode increases rapidly because it is proportional to the squared thickness of the active layer. To overcome this problem, we have increased the total thickness of the active layer using the BG layer, thus creating the strong built-in electric field. This field is sufficient to accelerate photoelectrons to saturation velocity [1], boosting the photoelectron's 'slow' diffusion to a 'rapid' drift. Our estimate shows that it takes ~ 3 ps to extract photoelectrons from the BG layer and to inject them into the GaAs emitting layer. Therefore, use of a BG layer confers a low response time to the photocathode. To check the effectiveness of the BG layer to suppress the 'hot' electron contribution, we have measured the LEDC for the photocathode with a composite active layer, as shown in fig. 6 (b). One can see from this figure that the 'hot' electron contribution in this photocathode is much less than those measured for the photocathode with a HM active layer. The similar data, shown in fig. 7 (a), (b), were obtained for these two photocathodes at LN_2 temperature. One can see, also, that the cooling of NEA – photocathode increases the width of the photoelectron energy distribution due to the increase of NEA – value.

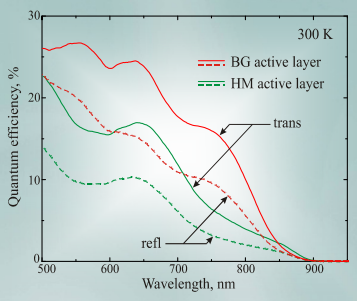

Fig. 4 – *Q.E.* Spectra for RM & TM geometries

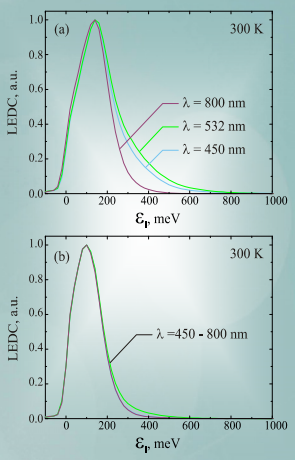

Fig. 5 – Reflection mode geometry

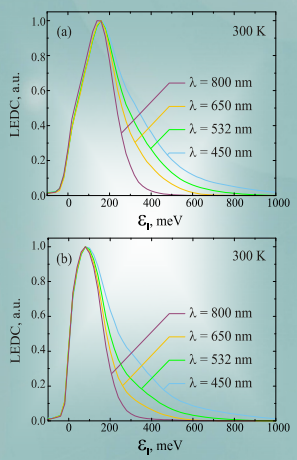

Fig. 6 – Transmission mode geometry

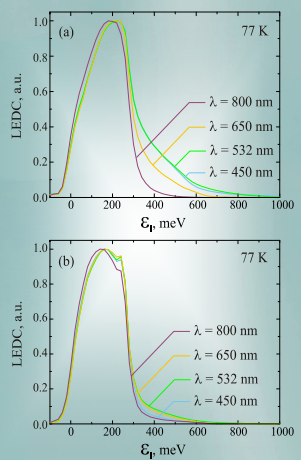

Fig. 7 – TM geometry at LN_2 temperature

Summary

A new design for a cooled transmission mode (TM) NEA photocathode on a sapphire base plate with a composite active layer, appropriate for FEL applications, is proposed and realized. To suppress the contribution of 'hot' photoelectrons in the broadening of the photoelectron energy distribution *without* loss of photocathode time response, a 'thick' band-graded (BG) layer with a strong built-in electric field was incorporated in the photocathode semiconductor structure. The estimated response time does not exceed 10 ps and quantum efficiency (*Q.E.*) at $\hbar\omega = 2.32$ eV exceeds 20%. Future plans include optimization of the band-graded active layer parameters and measurement of response time.

Literature

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