ENERGY ANALYSIS OF ELECTRONS EMITTED BY A SEMICONDUCTOR PHOTOCATHODE

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Abstract

In this paper we present measurements of the longitudinal energy spread $\Delta E_{\|0}$ of electrons emitted by a $In_{0.46}Ga_{0.54}As_{.06}P_{.94}$-photocathode with current densities up to 20 mA/cm^2. Furthermore we present a method of measuring the mean transverse energy $\langle E_{\perp 0}\rangle$ making use of adiabatic invariants for the electron motion in a decreasing longitudinal magnetic field. It was successfully tested with an electron beam emitted by a thermocathode and will soon be used to measure $\langle E_{\perp 0}\rangle$ for the photoelectrons, expected to be considerably smaller than for thermal electrons.

1.INTRODUCTION

High quality electron beams needed for electron cooling devices are characterized by small temperatures $T_{\|}$ and $T_{\perp}$. These can be reduced significantly by using a cold semiconductor photocathode with negative electron affinity (NEA) instead of a thermocathode employed in present devices and by accelerating these electrons adiabatically [1]. In the last few years it was demonstrated by different groups [2,3] that continuous currents of about 1mA, needed for an electron cooling device with a photocathode, where the beam diameter is 2mm [4], can be produced with a lifetime of several weeks. If the semiconductor photocathode is precleaned in a separate chamber and brought into the ultrahigh vacuum gun chamber using a fast entry lock system [2], reproducible quantum efficiencies (QE) of about 25% are reached without problems.

However, no systematic measurements concerning the initial longitudinal energy spread $\Delta E_{\|0}$ and the initial mean transverse energy $\langle E_{\perp 0}\rangle$ of the electrons emitted by a semiconductor photocathode were published until now. In contrast to a heated thermocathode, where $\Delta E_{\|0} = \langle E_{\perp 0}\rangle = k_B T_{cath}$, it will be shown in this paper for current densities relevant for an electron cooling device that the energy spread of electrons emitted by a NEA-photocathode is not only determined by the temperature of the cathode T_{cath} but also strongly dependent on the NEA condition.

2. LONGITUDINAL ENERGY DISTRIBUTIONS AND $\Delta E_{\|0}$

The experimental setup is presented in fig.1. The photocathode (1) is a lattice-matched InGaAsP epitaxial (111)A-layer, grown on (100) GaAs by liquid phase epitaxy and p-doped with Zn to $5 \cdot 10^{18}/cm^3$. It is activated to NEA by covering it with small amounts of Cs and NF_3 in ultra high vacuum; then the vacuum level lies below the conduction band minimum in the bulk and electrons lifted from the valence to the conduction band can leave this cathode. The InGaAsP-photocathode has a better stability than a GaAs-photocathode; according to [2] this is caused by the higher band gap of E_g= 1.89eV (measured by photoluminescence) as compared to E_g= 1.42eV for GaAs. The Pierce-electrode (2) with a hole diameter of 2 mm determines the diameter of the electron beam. The first anode (3) is situated 2mm in front of the cathode, the second anode (4) is kept on ground potential - therefore the electron energy is always given by the negative cathode voltage U_{cath}.

After leaving the cathode, the electron beam is guided in a longitudinal magnetic field of **B**= 1400 Gauss, produced by a pair of Helmholtz coils. This high field strength ensures that the relaxation of transverse energy into longitudinal energy is suppressed [1]. A 3-plate retarding-field energy analyzer (5), moveable in transverse direction, is located at a distance of 4 cm in front of the cathode to measure the longitudinal energy distribution $f(E_{\|})$ of the electron beam. Using a 25 μm pinhole in the entrance diaphragm only a 10^{-4} fraction of the beam is analyzed. The collector current I_{coll} detected on the third plate as a function of the retarding voltage U_{ret} on the second plate gives the integrated electron distribution curve (EDC). The differential signal is obtained online via lockin-technique. Both voltages U_{cath} and U_{ret} were produced by batteries to avoid voltage ripple and are monitored continuously with differential voltmeters (accuracy 0.5meV).

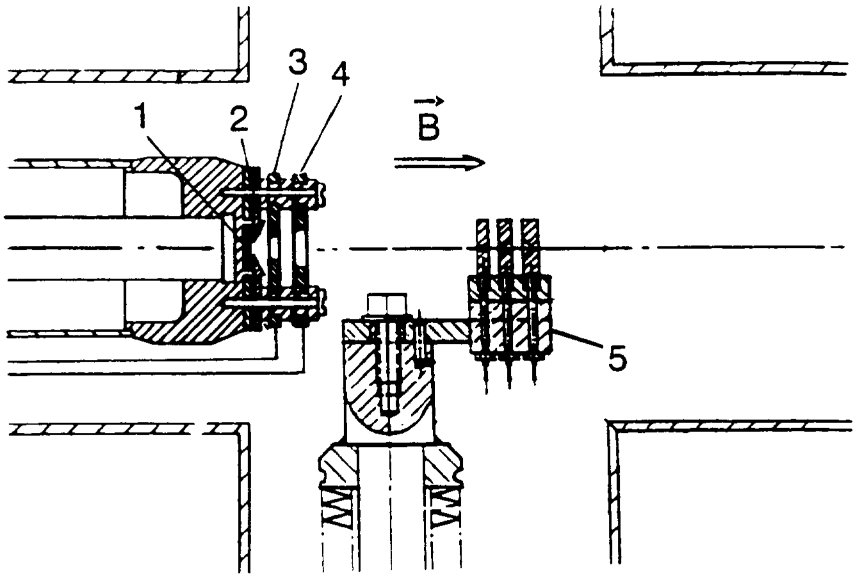

fig.1: Experimental setup with electron gun and retarding field energy analyzer (for further explanations see text).

Prior to the experiments with the NEA-photocathode, the system was tested with an electron beam produced by a conventional thermocathode. EDCs for four different currents of the thermocathode are presented in fig.2a in a semilogarithmic plot. As the gun is operated in space charge limitation, the mean energy of the electron beam decreases with increasing current: the potential produced by the space charge plasma directly in front of the cathode acts as a low energy cut-off [5]. Due to the strong magnetic field, the small current density (maximum 0.4mA/cm^2) and the low kinetic energy ($\approx$ 7eV) of the extracted electron beam, the energy distributions $f(E_{\|0})$ of the emitted electrons are not substantially affected by relaxation processes [1]. Thus we have for the distribution measured by the retarding field analyzer $f(E_{\|}) \approx f(E_{\|0})$ and $\Delta E_{\|} \approx \Delta E_{\|0}$. Therefore all EDCs have the same asymmetric exponential shape. As the main part of the longitudinal energy $E_{\|}$ is distributed proportional to $\exp(-E_{\|}/k_B T_{cath})$, it is possible to determine $k_B T_{cath}$; the deduced value of 98 ± 2meV is in very good agreement with pyrometer measurements. The energy spread $\Delta E_{\|} = \sqrt{\langle E_{\|}^2 \rangle - \langle E_{\|} \rangle^2}$ for each curve is $\Delta E_{\|} \approx$ 102meV which also agrees with $k_B T_{cath}$.

The EDCs of photoelectrons produced by illuminating the photocathode, held at room temperature, with 30μW of a single-mode HeNe-Laser are shown in fig.2b. Again the current densities are very small (between 3 and 30μA/cm^2) so that the EDCs reflect the longitudinal energy distributions of the electrons leaving the cathode f($E_{||}$)$\approx$ f($E_{||0}$), $\Delta E_{||} \approx \Delta E_{||0}$. For the measurement shown in fig.2b the electron gun was operated in the current limited regime (both anodes are grounded) and the different current densities are obtained after different aging times (indicated in fig.2b) of the activated photocathode. Aging is caused by pollution of the activated surface by components of the residual atmosphere which leads to an increase of the vacuum level (decrease of NEA and QE) that acts as a low energy cut-off. Due to this aging the photocathode has a so called 'dark' lifetime of about two days. Subsequent reactivations to the initial maximum NEA are possible by recesiation. The left curve in fig.2b (0min), measured after activating the cathode to highest NEA and QE, is rather broad ($\Delta E_{||} \approx$ 110meV). When NEA and QE get smaller, the EDCs become narrower (down to $\Delta E_{||} \approx$ 48meV).

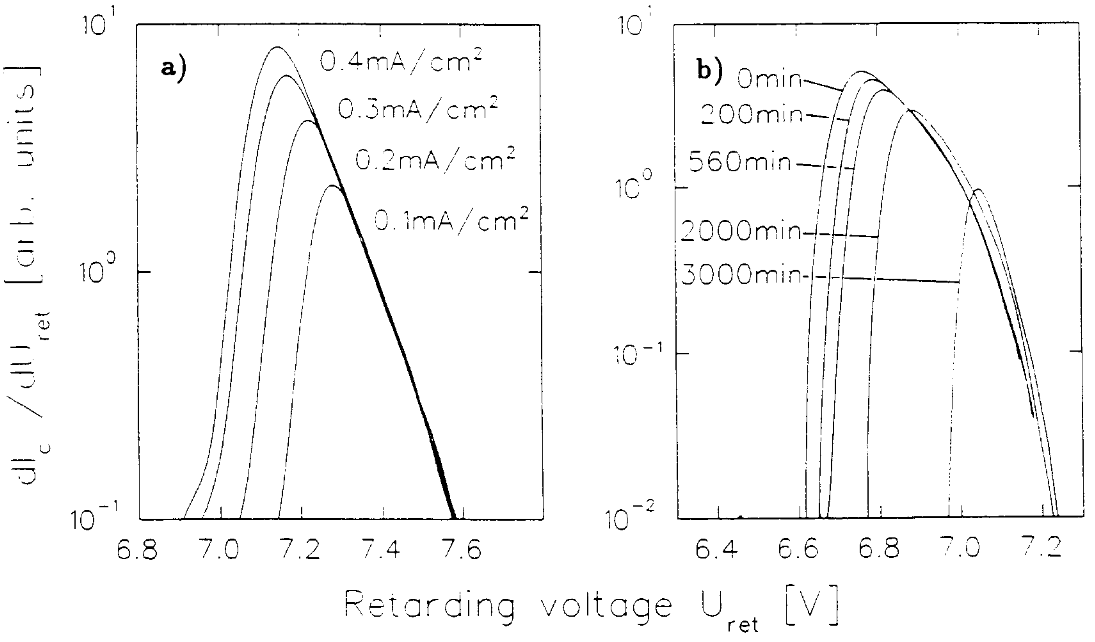

fig.2: Longitudinal EDCs measured for electrons produced a) by a thermocathode at different current densities and b) by the $In_{0.46}Ga_{0.54}As_{.06}P_{.94}$-photocathode at different aging times.

Comparison of the EDCs shown in fig.2a and fig.2b reveals a basic difference between thermo- and photocathode: the longitudinal energy spectra of the emitted photoelectrons do not have an exponential high energy slope. Hence the widths $\Delta E_{||}$ of these EDCs are not constant but they mainly depend on the potential (height of vacuum level) that the electrons have to overcome before they leave the cathode. Only in the case of very small NEA the slope of the EDC is exponential and T_{cath} as well as the photonenergy has a substantial influence on $\Delta E_{||0}$, for example $\Delta E_{||0}$ $\approx$25meV at $T_{cath} = 150K$ and hν=2eV.

We measured the same non-exponential EDCs as shown in fig.2b when the photocathode had a constant (e.g. maximum) NEA but the gun was operated in space charge limitation. This is an important result because it shows that the electrons do not thermalize in the space charge region before they leave it.

One of the aims of these experiments was to determine $\Delta E_{||0}$ for current densities used in an electron cooling device. Therefore the photocathode was illuminated with 30mW emitted by a single mode dye-laser, U_{cath} was set to -100V and the current was extracted in space charge limitation. The measured $\Delta E_{||}$ is plotted as a function of the current density in fig.3 (dots). Due to the high kinetic energy E_{kin}, relaxation of potential energy [1] in the accelerated beam already leads to a substantial energy broadening at current densities as low as 0.2mA/cm^2. Thus the originally asymmetric EDCs displays a Gaussian shape and the measured width $\Delta E_{\|}$ is larger than $\Delta E_{\|0}$ according to [1]:

$$k_B T_{\|} = \frac{(\Delta E_{\|})^2}{2E_{kin}} = \frac{(\Delta E_{\|0})^2}{2E_{kin}} + 2\langle E^{Relax}\rangle \ , \qquad 2\langle E^{Relax}\rangle = Ce^2 n^{\frac{1}{3}}$$

$\langle E^{Relax}\rangle$ is the mean relaxed potential energy in the rest frame, n the electron density and C a value between 0 and 1.3, depending on the number of plasmaoscillations n_{osc}, the electrons experienced on their flight to the retardation analyzer; C is a constant of about 0.7 for a nonadiabatically accelerated beam if n_{osc} is larger than one [1]. In our setup the flight time is very short and n_{osc} is smaller than one for current densities below 10mA/cm^2. To determine C, we measured $\Delta E_{\|}$ as a function of n for an electron beam emitted by the thermocathode using the upper formula and $\Delta E_{\|0} = 97$meV.

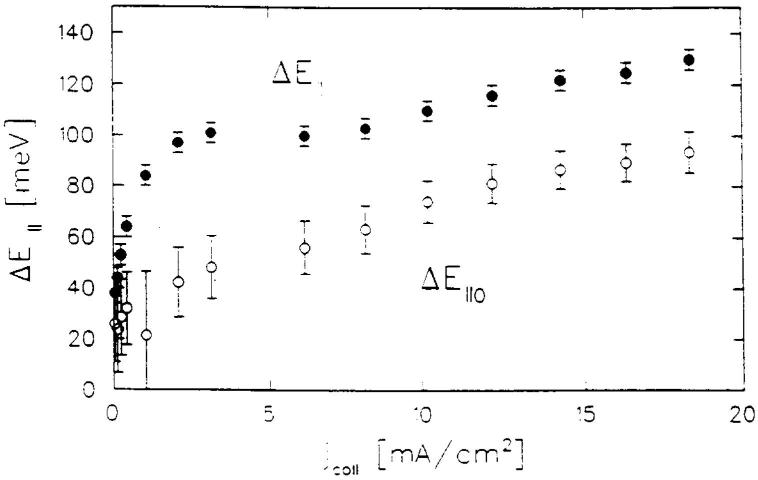

fig.3: Measured energy widths $\Delta E_{\|}(\bullet)$ and deduced original widths $\Delta E_{\|0}(\circ)$ for different electron current densities emitted by the InGaAsP-photocathode.

The deduced widths $\Delta E_{\|0}$ for electron beams emitted by the photocathode is shown in fig.3 (circles). The situation is very similar to that shown in fig.2b; if the majority of the electrons lifted to the conduction band are not emitted because they are prevented from leaving the cathode by the vacuum level or by the space charge potential, $\Delta E_{\|0}$ is rather small. By reducing this potential, the emitted current and $\Delta E_{\|0}$ increases. Note that even at current densities of 20mA/cm^2 $\Delta E_{\|0}$ is smaller than 100meV, i.e. $\Delta E_{\|0}$ does not exceed the initial energy spread of electrons from a thermocathode.

3. MEASUREMENT OF THE MEAN TRANSVERSE ENERGY $\langle E_{\perp 0}\rangle$

In a proper accelerated electron beam, guided in a constant longitudinal magnetic field, the transverse temperature $k_B T_\perp$ is equal to the initial mean transverse energy $\langle E_{\perp 0}\rangle$ of the electrons. The great advantage of a cooled semiconductor photocathode in contrast to a heated thermocathode is a small $\langle E_{\perp 0}\rangle$; if the tangential component of the electrons momentum is conserved when they cross the interface between crystal and vacuum (like in UPS and XPS experiments), $\langle E_{\perp 0}\rangle$ is expected to be as small as 1meV due to the small effective mass of the electrons inside the semiconductor [6].

All experiments concerning $\langle E_{\perp 0}\rangle$ [6,7,8,9] measured the angular distribution of the emitted electrons but could not take into account space charge effects in the electron beam. Their results differ extremely (1meV $< \langle E_{\perp 0}\rangle <$ 120meV) and were never compared with measurements of

the well known $\langle E_{\perp 0}\rangle$ of a thermocathode. We have developed a technique for measuring $\langle E_{\perp 0}\rangle$ with an accuracy of 3meV independently of any spacecharge and relaxation effects.
For these measurements the distance between cathode and analyser (see fig.1) is increased to 26cm. Moreover, the longitudinal magnetic field $\vec{B}$, produced by three pairs of magnetic coils, decreases in a defined way (see fig.4a) from $\vec{B}_0$ (at the cathode position) to $\vec{B}_a$ (at the analyzer position). The ration $\alpha = B_a/B_0$ can be varied between 1 and 0.5 with $B_0 = 1400$G. As the electron beam expanse adiabatically [10], the mean transverse energy $\langle E_\perp\rangle$ divided by B is a constant of motion. From the energy conservation law $\langle E_{\perp 0}\rangle + \langle E_{\|0}\rangle = \langle E_\perp\rangle + \langle E_\|\rangle$ it follows that the mean longitudinal energy of the electron beam at the analyzer position $\langle E_{\|a}\rangle$ increases proportional to (1-α): $\langle E_{\|a}\rangle - \langle E_{\|0}\rangle = (1-\alpha)\langle E_{\perp 0}\rangle$. The change of the mean longitudinal energy $\langle E_{\|a}\rangle - \langle E_{\|0}\rangle$ can be measured with an error smaller than 1.5meV and thus $\langle E_{\perp 0}\rangle$ can be deduced.

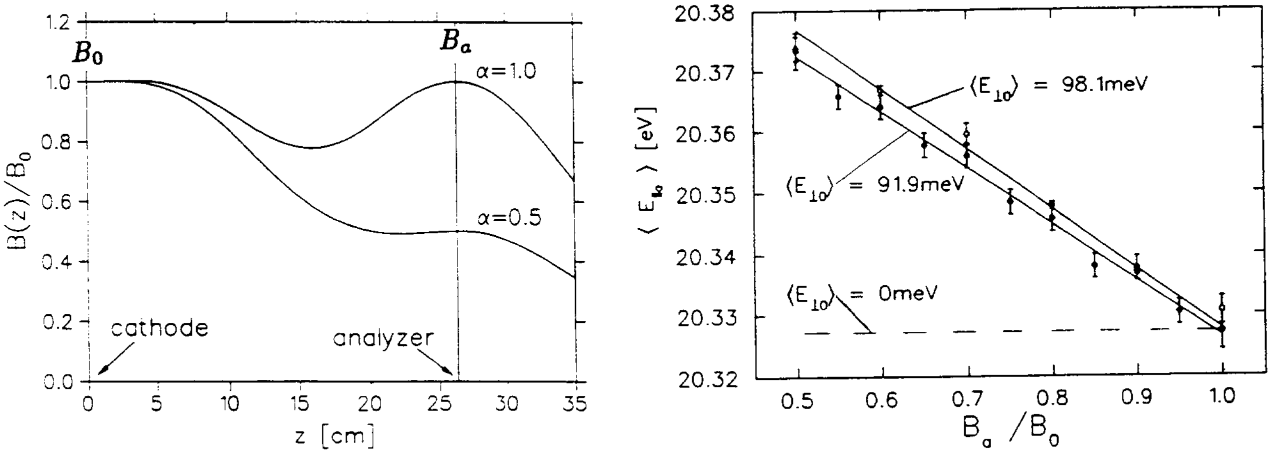

fig.4: a)Different field structures used for an adiabatic expansion of the electron beam.
In b) the measured mean energy of the electron beam $\langle E_{\|a}\rangle$ is plotted as a function of B_a/B_0 for two different T_{cath}. The broken curve would be obtained for $\langle E_{\perp 0}\rangle = 0meV$.

In fig.4b $\langle E_{\|a}\rangle$ is plotted as a function of B_a/B_0 for two different temperatures of the heated thermocathode, T_{cath}=1070K (•) and T_{cath}=1150K (○). From the slope of the fitted curves it is possible to deduce $\langle E_{\perp 0}\rangle$ with an error of 3meV, which is in very good agreement with $k_B T_{cath}$ for both curves. Corresponding measurements of $\langle E_{\perp 0}\rangle$ for InGaAsP- and also for GaAs-photocathodes are in progress.

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