Semiconductor Photocathodes

EEE 538 Term Paper

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Ben Buckner

Introduction

Hertz discovered the photoelectric effect over a century ago, even before the discovery of the electron itself. Since the subsequent recognition of the true nature of photoemission, photocathodes have used this effect to produce free electrons for a variety of applications including infrared viewing systems, particle accelerators, and electron microscopes.

The first photocathodes were composed of metals, but it was eventually found that other materials can provide significant advantages in quantum efficiency and minimum excitation wavelength. Semiconductors in particular have been found to be particularly useful because of the facility with which their electronic properties may be controlled.

Photocathode Apparatus

Apparatus using photocathodes consist of the photocathode, a light source, and an anode, usually of metal.

These devices almost always operate in a vacuum. The more obvious reason for this is that the electron mean free path through a gas at atmospheric pressure is extremely small such that emitting free electrons into air is not particularly useful. The less obvious reason is that many photocathode materials are quite sensitive to contamination and often suffer drastic reductions in their efficiency on exposure to many common substances like water and nitrogen. Even thermionic or hot cathodes are subject to this. Indeed even allowing vacuum levels to rise from 10^{-10} up to 10^{-7} Torr can reduce quantum efficiency of Cs_2Te photocathodes by a factor of 3.[1] Consequently, much recent research focuses on finding materials which are more resistant to contamination or on the use of thin films to passivate and protect the photocathode surface.[2]

Two basic configurations are encountered, reflection photocathodes and transmission photocathodes (Fig. 1).

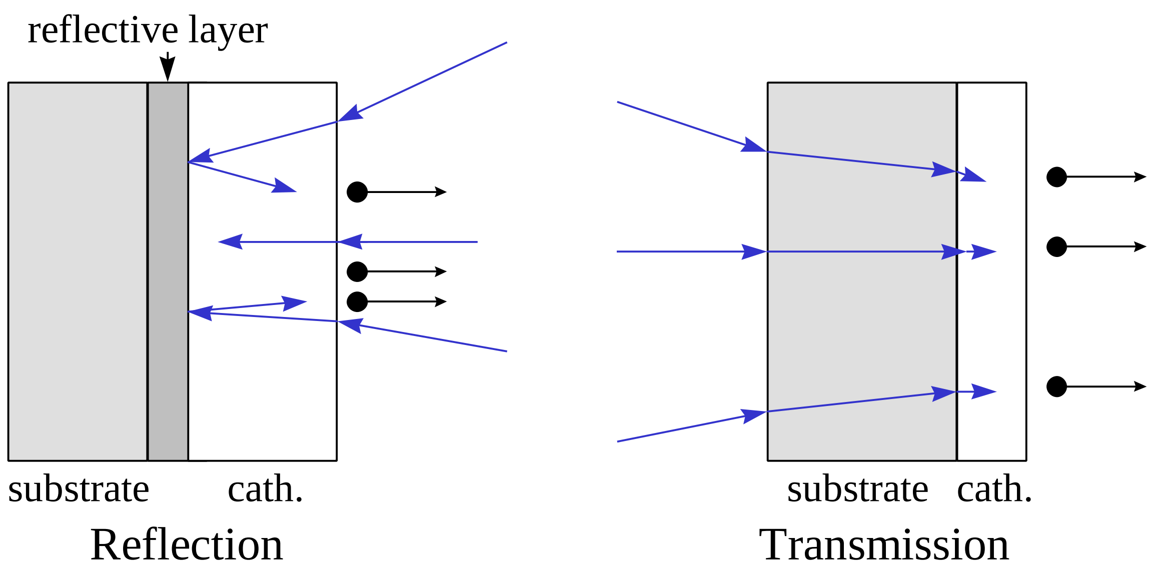
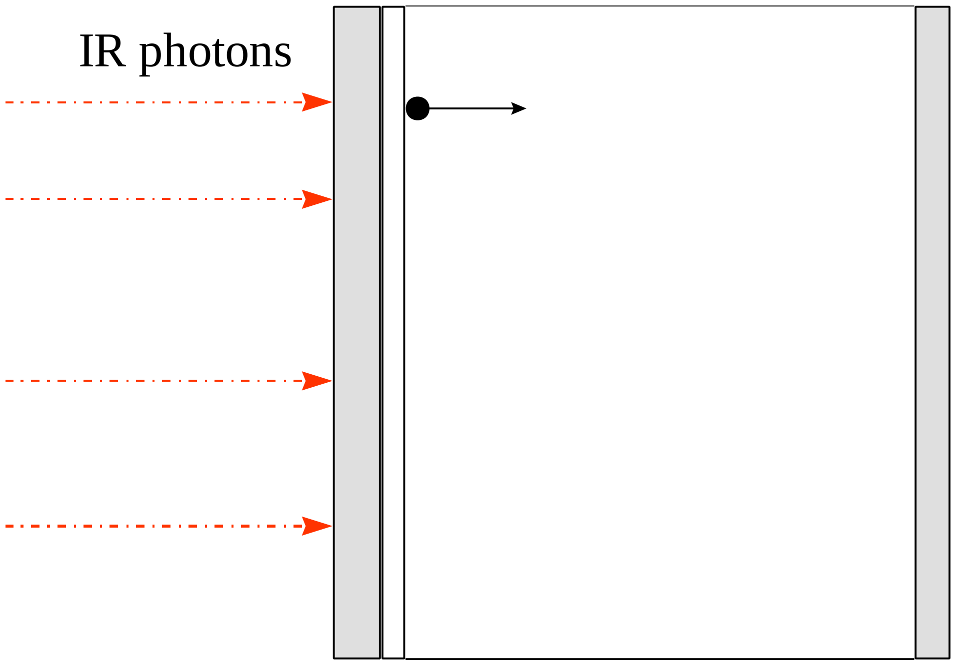
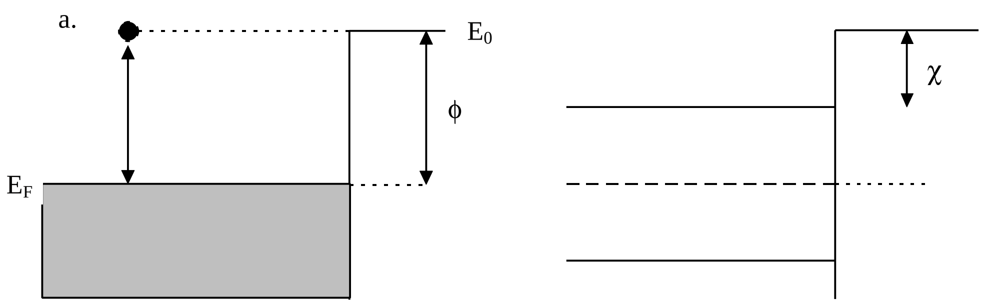


Figure 1. Photocathode configurations (after Johnson[3]).

Reflection devices are most often encountered in applications which simply require an electron source to produce a focused beam of electrons as in an electron microscope or synchrotron. In these, the light is incident from the direction of desired emission and a reflective layer lies directly under the cathode layer so that any illumination penetrating to that depth is reflected and can produce additional photoelectrons on the way back. Transmission devices are usually found in applications where the photoelectrons are intended to produce an image on a phosphor screen corresponding to the pattern of radiation incident on the substrate side of the cathode (Fig. 2). Such devices require a judicious choice of substrates to allow the radiation to penetrate while fulfilling the physical requirements of the substrate.


IR photons



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generated within roughly the mean free path distance from the surface can contribute to the electron emission current.

However, with surface treatment, some semiconductors can give electron affinities which are effectively negative, such that the vacuum level actually lies below the bulk conduction band edge in energy. Fig. 4 illustrates this phenomenon.

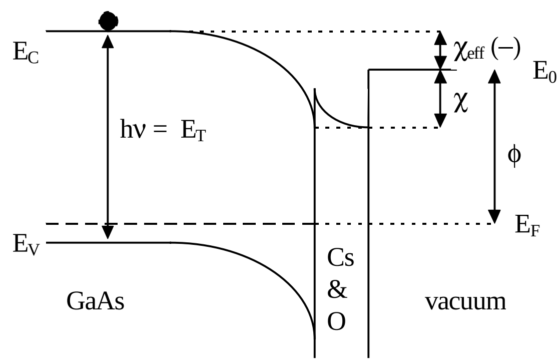

Figure 4. Photoemission from a Negative-Electron-Affinity Semiconductor (after Feigerle *et al*[5])

For these structures with negative electron affinity (NEA), the electron only needs to be photoexcited up to the conduction band edge, at which level it can be transported until just before reaching the surface. This eliminates the requirement that the electron avoid scattering events during transport from the generation site.

The electron mean free path still has an effect however. The NEA effect results from Fermi-level pinning by surface states, and this pinning causes the bands to bend downward, changing the relative positions of the CB edge and E_0. Obviously, if the electron mean free path is short compared to the depletion width at the surface, the electron will follow the CB downward as it loses energy in scattering events and become trapped in the small well at the surface. On the other hand, for a longer mean free path, the electron will remain at the level of the bulk CB as it passes through the depletion region and thus pass easily into the vacuum. Because of this limitation on the depletion width, NEA photocathodes are very heavily p-doped in order to keep the depletion width small.

NEA then gives two important benefits. First, because the electron only needs to be excited to the CB, the threshold photon energy required for emission is only $E_T = E_G$ rather than $E_T = E_G + \chi$ as in non-NEA devices. Second, and perhaps more importantly, the depth from which electrons may escape the surface (the "escape depth") is determined by recombination lifetime rather than the mean free path.

When no bias is maintained across the semiconductor itself, the electrons are transported to the surface by diffusion alone so that the diffusion length L_n is effectively the depth limit for the generation of photoelectrons. This is of course typically much longer than the mean free path. For GaAs, the most common NEA photocathode material, the mean free path may be around0.0060 μm [6] while the diffusion length may be 1 μm.[7] This greatly enhances the quantum yield of the device.

Materials

Most semiconductor photocathode materials fall into two categories, alkali and multialkali materials including Cs_2Te, Cs_3Sb, and CsK_2Sb, and III-V semiconductors like GaAs and InGaAs, plus various III-V heterostructures. Multialkali photocathodes typically have low electron affinities, a characteristic of alkali metals, but do not display the negative electron affinity. III-V semiconductors by themselves do not have remarkably low electron affinities, but when treated with various combinations of Cs and other materials can display the NEA effect.

Negative Electron Affinity Devices

Negative electron affinity is most often obtained by applying a thin layer of Cs or alternating layers of Cs and O_2 to p-GaAs, though it has been seen in related III-V systems and even in Si[8]. Despite this system's having been known for over 30 years, there are still a number of questions being addressed as to the exact nature of the states at the surface and at the GaAs/Cs-O interface. In particular, the dependence of the position of the pinned Fermi level is still in question and the failure of a large proportion of electrons to transport through the depletion region was investigated by Gerchikov and Subashiev as recently as last year.[9] They predict quantum yield resonances depending on depletion width as a result of the bound states formed within the potential well at the Schottky barrier.

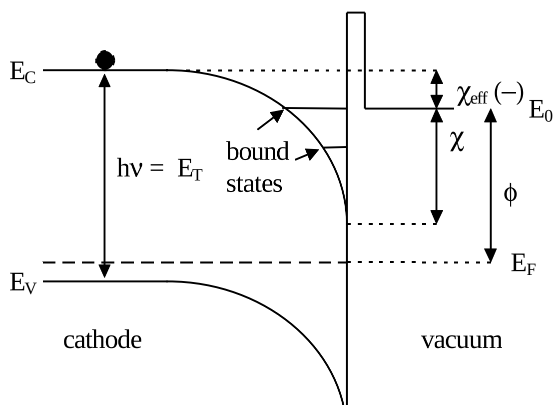

Figure 5. Bound states at interface in Gerchikov and Subashiev's energy band model (ref. 9).

NEA photocathodes display a number of useful properties even beyond the improved quantum efficiency that results from better transport and the reduction of threshold energy to E_G. For one, the electron beams produced can have both narrow energy distributions at high intensity and significant degrees of spin polarization.

Feigerle *et al.* demonstrated in 1984 that electron beams from NEA GaAs could have monochromaticity comparable to that obtained by passing thermionic beams through electron monochromators while maintaining currents several orders of magnitude larger than the filtered beams.

Photoelectrons from unstrained GaAs itself can be polarized to maximum of 50% polarization (polarization is the difference between the numbers of electrons in each spin state divided by the total number of electrons),[10] though achieving more than 30% is difficult and efficient polarization requires longer excitation wavelengths which tend to reduce quantum yield. Maruyama *et al.* have found that introducing aluminum to produce AlGaAs (and reduce the bandgap) can give good polarization at shorter wavelengths, but with the semiconductors. This barrier is then reverse biased. The drawback to field-assistance is that it enlarges the depletion region to the point where the normal NEA transport effect is no longer operational, but it seeks to provide sufficient energy from the field to offset this.[15] Another drawback is that this tends to enhance dark current,[16] but that is generally only of great concern in photodetector applications. Bell *et al.* demonstrated a field-assisted InP device in which transport occurred in a higher conduction-band valley than the minimum valley.[17]

Conclusions

While research into semiconductor photocathodes enjoyed its greatest flourishing in the late 1960s and early 70s, the increasing applications for electron beams have led to new interest in their unusual properties and in methods for making them less sensitive to operating conditions. Since electron beams have such an important role in nanotechnology, this renewed interest can be expected to increase as nanotechnology continues to push into smaller and smaller scales.

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