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Improving the energy spread and brightness of thermal-field (Schottky) emitters with PHAST—PHoto Assisted Schottky Tip

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ABSTRACT

Using a relatively simple model of photoemission we derive an expression for the reduced on axis brightness of a thermal-photofield emitter. We then show that it is theoretically possible to reduce the energy spread of a Schottky (thermal field) emitter whilst increasing the reduced brightness. This can be achieved by the illumination of the tip with a high intensity laser light. We call the source PHAST—PHoto Assisted Schottky Tip. We find that due to the strong E-fields applied PHAST may operate at photon energies below the (Schottky reduced) work function. Thus removing the need for UV lasers, we will show that it is in fact preferable to work in the red, or in the green. The necessary laser intensities probably limit the application to pulsed operation.

1. Introduction

The Schottky electron source (tungsten needle thermal-field emitter with a layer of ZrO_x, see Fig. 1) is used for many SEMs, TEMs, Auger spectrometers and semiconductor inspection tools. Electron emission arises due to a combination of thermal and field effects. The ZrO_x lowers the work function of the tungsten to about 2.9 eV. Schottky sources are normally operated at fields between 0.4 and 1.0 V/nm, provided by an extractor plate in front of the tip. A temperature of approximately 1800 K is obtained from resistive heating. Typical parameters are an energy spread between 0.3 and 0.8 eV full width 50 (FW50) and an experimentally measured reduced brightness of 10^7 A/m^2 sr V [1]. The brightness is a key concept in optics, and it measures the current density per solid angle. Unfortunately the brightness is not invariant to an accelerating/decelerating voltage and so we use the brightness per volt; this quantity is called the reduced brightness. Energy spread and reduced brightness are limiting factors in many applications. It has been shown [2,3] that for many situations the reduced brightness and energy spread uniquely determine the amount of current that can be focused into a spot of a particular size.

We intend to control energy spread and/or increase the reduced brightness by illuminating a Schottky tip with a laser. Thus making a "PHoto Assisted Schottky Tip"—PHAST.

In the rest of this paper we will first bring together Shimoyama's work [4] and the Fowler–Dubridge method [5–7] to derive equations for the reduced brightness of a photoemitter. This will be the main topic of Section 2.1 but it will also include current density calculations which are useful when comparing theory to experiment. Section 2.2 will give an equation to find the energy spread. In Section 2.3 we will discuss the Fowler–Dubridge method and what we call Fowler's approximation. Section 2.4 gives a short overview on how we deal with the transmission coefficient, and Section 2.5 is on scattering in metals. Section 3.1 will include a comparison of our theory to experimental and analytical results. In Section 3.2 we will use our model to show that PHAST can improve the reduced brightness and energy spread of a Schottky emitter. Finally we will have a discussion about the usefulness of PHAST and make some conclusions.

2. Introduction to PHAST

The basic concepts of PHAST emission are schematically shown in Fig. 2. For most cathodes electrons can escape by any of the three basic processes: thermal emission over the top of the barrier (see Fig. 2); field emission by tunneling through the barrier; or

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photoemission, where an electron interacts directly with a photon and escapes over the barrier. In the present situation we have a strong field, a high temperature and a focused laser beam applied to the tungsten tip as shown in Fig. 1. This means that we can have emission by combination of any of the three previously mentioned inputs.

(1) The strong field will act to lower the barrier (see Fig. 2); this is the Schottky effect [8]. The barrier shape changes as shown in Fig. 2 for a field strength of 1 GV/m. If the field is strong enough the barrier will become thin enough for electrons to tunnel through.

(2) The high temperature changes the energy distribution of the electrons giving it a long tail at higher energies. Some of the electrons in the tail will have an energy above the barrier height and can then escape. This may be assisted by the Schottky effect, which will reduce the temperature required for a particular current. Thermally excited electrons may also tunnel through the top of the barrier where it is thin enough.

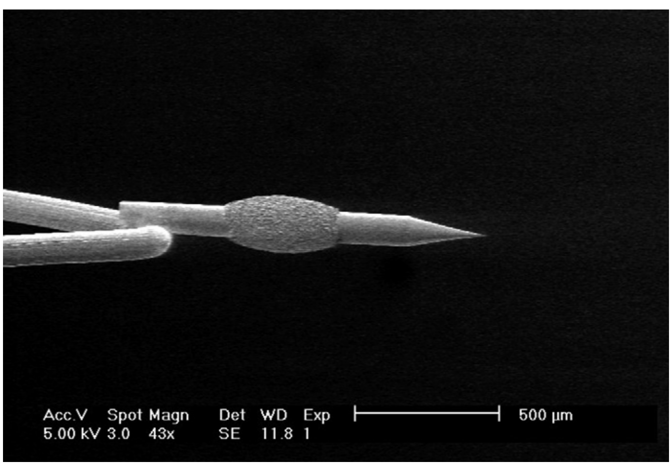

Fig. 1. Electron microscope picture of a standard Schottky tip, the lump is the ZrO_x reservoir. The legs are for heating.

(3) Finally, the focused laser beam (ignoring any thermal aspects) will promote electrons to higher energy levels. The electrons can then do one of the three things: (i) escape directly; (ii) escape in combination with their prior thermal energy; or (iii) they may be photoexcited and then tunnel if there is sufficient field.

We want to use the three inputs to maximize the output of PHAST for the highest brightness and lowest energy spread.

We will need equations to describe the reduced brightness and energy spread. We will also want equations for the quantum efficiency/current density so that we might compare our model to experimental results. For thermal-field emission these are well documented in textbooks and in the literature, see for example [9,10]. Photoemission literature is often based on the Fowler–Dubridge model [5,6]. With this we may calculate energy spreads, and currents or quantum efficiencies and even account for multi-photon excitation [11]. However, up to now the Fowler–Dubridge model does not include a method of finding the brightness. This is what we will now do.

2.1. Brightness

To derive an expression for the reduced brightness from a photoemission source we will start by looking at the work of Shimoyama [4]. We will follow part of his derivation of brightness for a thermal-field emitter. Then we will combine Shimoyama's work with Jensen's work on photo (field) cathodes (see for example [7]).

According to Shimoyama [4] to derive a complete (at every point in space) expression for the brightness, we must ray trace the emitted electrons. The full expression for brightness is shown in Eq. (1) and illustrated in Fig. 3:

$$B(r,\theta) = \frac{d^2 I(r,\theta)}{d\Omega \, dS \cos\theta} \tag{1}$$

Here r and θ refer to coordinates on a cylindrical coordinate system, I is the current, dS a cathode surface element, $d\Omega$ is the solid angle element, and θ the angle normal to dS. For some cases, analytical solutions can be found in Eq. (1), but not in general, and

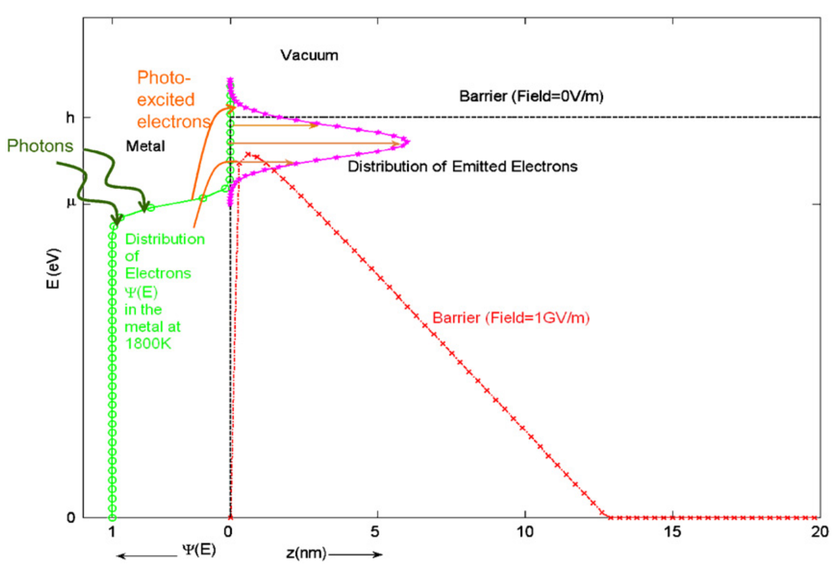

Fig. 2. Schematic description of the emission processes contributing to PHAST. The dashed and × marked lines show how the barrier shape changes with the introduction of a strong E-field; this allows tunneling to occur. In the case of a Schottky emitter the tunneling is mainly from thermal electrons as the field is not strong enough to allow significant tunneling from around μ (the electron chemical potential). With PHAST we have the addition of photons which excite electrons from lower levels to (if available) an energy level $h\nu$ higher. These excited electrons have the possibility to escape either directly or by tunneling through the barrier. If the electrons are already thermally excited and are subsequently excited by a photon, and escape, then they become thermal photo (field) emitted electrons. The distribution of emitted electrons for PHAST is shown with the line marked with *.