

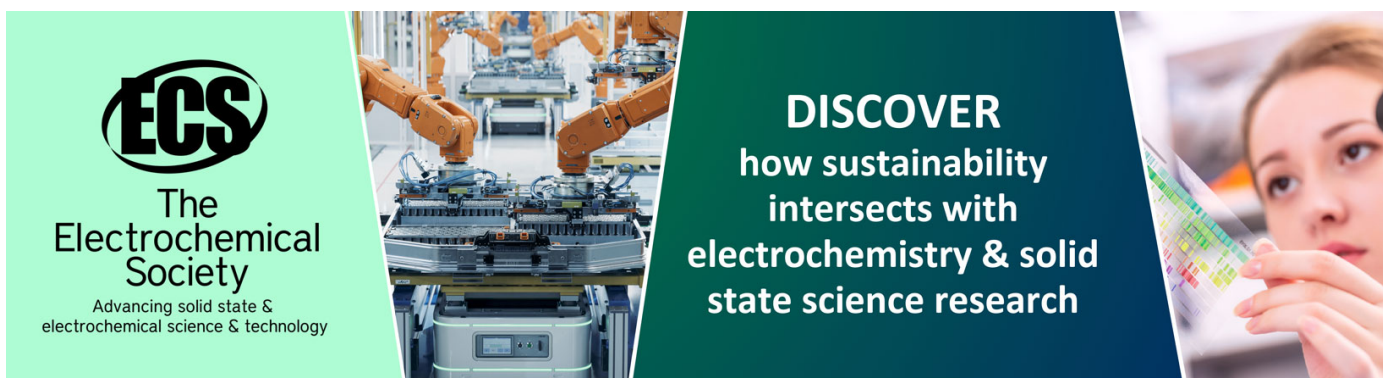
A diagnostic study of the field emission characteristics of individual micro-emitters in CVD diamond films

To cite this article: N S Xu *et al* 1994 *J. Phys. D: Appl. Phys.* **27** 1988

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A diagnostic study of the field emission characteristics of individual micro-emitters in CVD diamond films

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Received 31 May 1994

Abstract. Details are given of an experimental study of the characteristics of field-induced electron emission from 15 mm diameter CVD diamond films deposited on an Mo substrate. Three dedicated techniques have been used to characterize the electron emission process: (i) the 'transparent anode imaging' technique for recording the spatial distributions of emission sites and the total current–voltage (I – V) characteristic, (ii) the 'anode probe hole' technique for measuring the I – V characteristic of individual sites, and (iii) 'field emission electron spectroscopy' for studying the energy distribution of emitted electrons. Finally, the physical implications of the findings from the electron energy spectroscopy measurement are discussed.

With the rapid development of diamond film technology, there has been a growing interest in its potential application to the fabrication of cold-cathode electron sources. Indeed, there have been several studies of the field emission properties of thin film diamond structures [1–4]. In two such recent papers [1, 2], the present authors have reported on the use of a transparent anode imaging technique for studying the spatial distribution of emission sites on 12 mm diameter Mo cathodes coated with 5 μm thick CVD diamond films. These studies established that the first emission site generally 'turns-on' at macroscopic surface fields of around 3 MV m^{-1} , with more sites appearing as the applied field is further raised. At fields of 5 and 10 MV m^{-1} respectively, densities of detected emission sites were typically 10 and 60 from a 12 mm diameter CVD diamond film. Under these latter field conditions, the externally measured emission current was $\sim 100 \mu\text{A}$, with a total-cathode β -factor of ~ 250 . From a qualitative comparison of these findings with the emission characteristics of bulk carbon graphite, it was tentatively concluded that the localized emission centres observed in these studies were associated with the presence of graphite inclusions in the diamond films.

To gain a more detailed physical understanding of the emission mechanism responsible for the observed properties of diamond-coated cold cathodes, a high-resolution electron spectrometer [5] was employed to study the emission characteristics of individual sites.

With this facility, it has thus been possible to record single-site I – V characteristics, the associated field emission image and the energy spectrum of the emitted electrons. On the basis of the new data presented below, it has been possible to confirm the involvement of hot electrons in the type of emission process envisaged in a previously proposed physical model [1].

Figure 1 illustrates the integrated spectrometer facility used to analyse the test cathodes. As fully described elsewhere [5], this is a UHV system employing a hemispherical analyser, a step-motor-operated specimen holder, a phosphor screen for recording field emission images, deflector plates for generating energy-resolved emission images [6], and a microcomputer for controlling the whole system. In addition, test cathodes can be rotated through 180° for control studies using a combined transparent anode and video recording facility.

The test cathodes were identical to those employed in our earlier studies [4, 5], and were initially characterized using the *in situ* transparent anode facility referred to above; i.e. in terms of their total-cathode I – V characteristic, and the spatial distribution of their emission sites. Cathodes are next scanned in a raster pattern in front of the anode probe hole to generate a complementary computerized map of the emission sites [5]; i.e. so that any chosen site can be rapidly centralized on-axis for a detailed study.

The I – V characteristic of such a centralized site is recorded in terms of the variation of the emission site

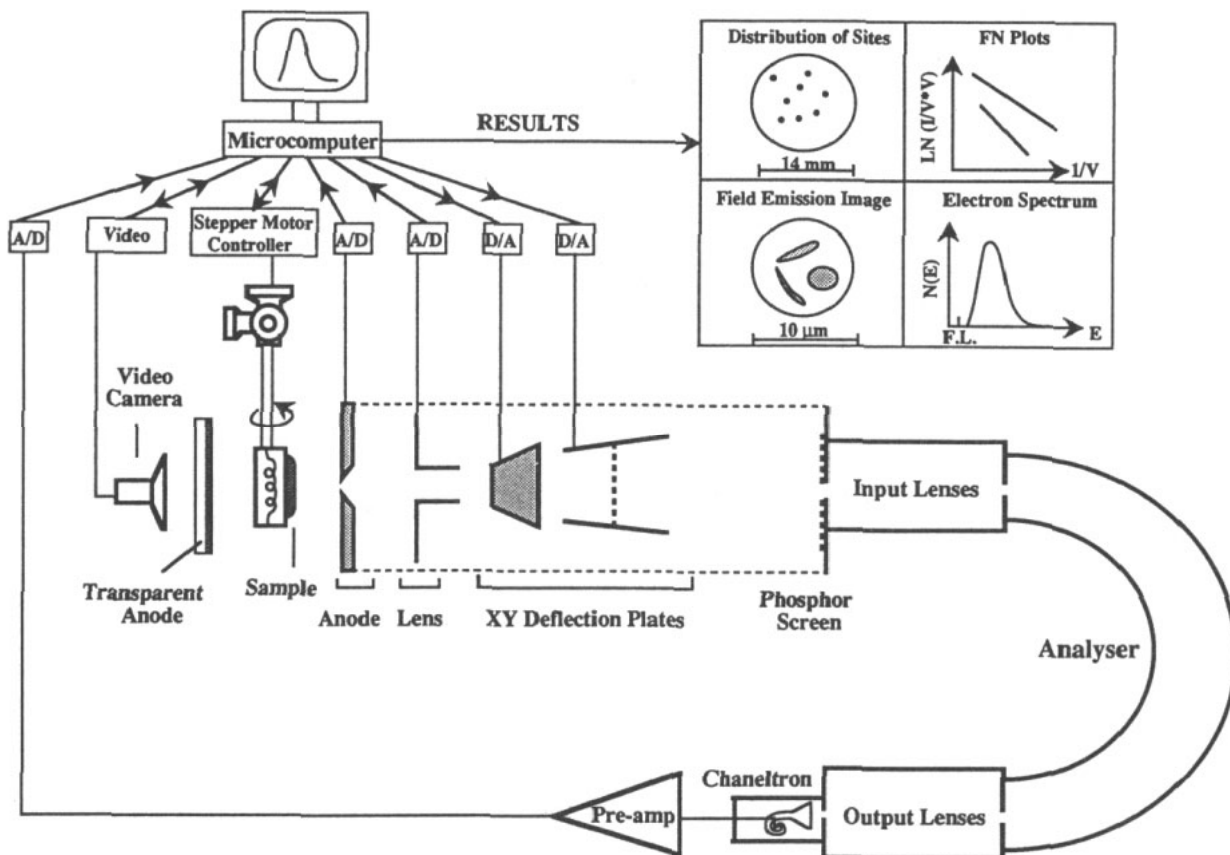


Figure 1. A schematic diagram of the field emission spectrometer facility used in the present study.

current transmitted by the probe hole as a function of the applied voltage [5]. Next, the intermediate electrostatic lens assembly is adjusted to produce a projection image of the emission on the phosphor screen painted on the entrance aperture of the analyser. With the aid of the sets of x - y deflector plates, any part of this image may then be located over the small central aperture in the screen, and the spectrum of the transmitted electrons recorded using a standard instrumental procedure [5].

As with previous studies, the analysis of a test cathode begins with the recording of the emission site distribution. Thus, figure 2 presents a typical site map recorded by the transparent anode imaging technique. The 'total' I - V characteristic of a test cathode can be recorded using this technique, and typically has the form shown as the 'total FN' in figure 3. For comparison, the I - V characteristic of a single site, recorded with an anode probe hole system, is shown as 'single-site FN' on the same figure. From these plots it will be seen that both curves have similar slopes, and therefore similar β -factors (typically 200–350).

Having thus aligned a suitable emission site on-axis, the intermediate electrostatic lens assembly is adjusted to obtain an emission image that may be directly photographed from the phosphor screen through a viewport in the specimen chamber. A typical example of an image obtained with these diamond-coated specimens is shown in the inset to figure 4, and is seen to consist

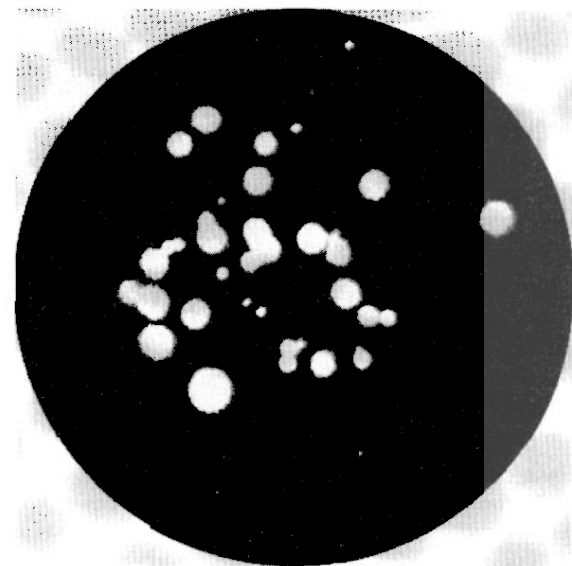


Figure 2. Spatial distribution of emission sites.

of seven sub-emission centres. The region of the image to be examined is next centralized over the 0.5 mm diameter entrance aperture of the spectrometer, and the spectrum of the electrons forming this part of the image is recorded. As will be seen from figure 4, such spectra are characterized by having a very broad single-peak

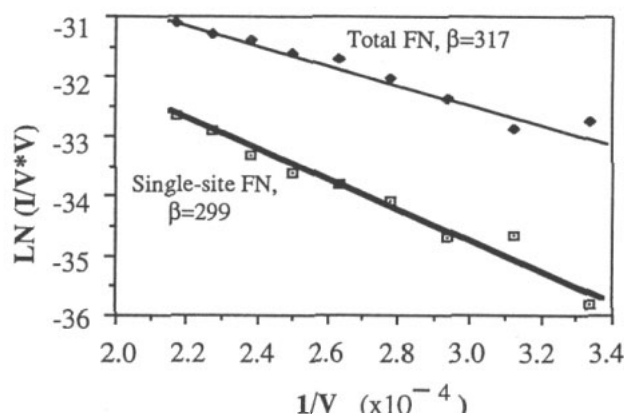


Figure 3. Comparison of 'single-site' and 'total' FN plots.

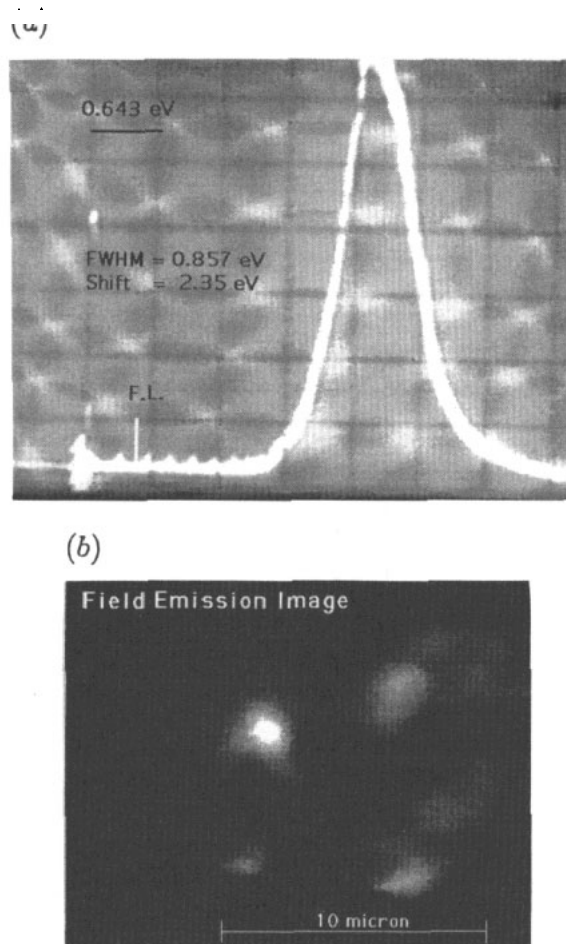


Figure 4. (a) A typical single-peak spectrum of the sub-emission centre at the top-left quadrant of the field emission image shown in (b). Both the spectrum and image were recorded at a field of 7.4 MV m^{-1} .

structure (FWHM of $\sim 1 \text{ eV}$), and a large shift from the Fermi level of the substrate cathode by 2–3 eV; however, it has also to be noted that there are significant variations in these spectral parameters according to the sampling region of the image.

On the basis of earlier findings [1,2], it was suggested that the localized point emission processes recorded in the map figure 2 are a property of graphite-

rich diamond films, where the individual emission centres are associated with composite graphite-diamond micro-regimes. However, because of the low β -factors measured for the total cathode emission current, i.e. typically ~ 250 , it was not thought that the emission originated from the tips of field-enhancing diamond crystallites. Instead, it was proposed that, through the antenna effect [7], embedded carbon particles facilitate the electroforming of conducting channels in the diamond crystallites. The concept of such channels was originally introduced by Mott and co-workers to explain the behaviour of MIM memory switches [8]. More recently it has been proposed that this same type of microstructure is responsible for the cold emission obtained from composite resin-carbon cathodes [9]. In the case of diamond-coated cathodes, it was also noted that the emission of electrons from such channels could be promoted by the possible negative affinity of the (111) crystalline planes. Equally, the electronic interface conditions established at the 'root' of the channels ensures the continuous supply of electrons from the underlying Mo substrate.

Compared with the narrow FWHM, i.e. typically $\sim 0.23 \text{ eV}$, of a clean tungsten tip, the broad spectral FWHMs ($\sim 1 \text{ eV}$) observed in this study strongly suggest that the emitted electrons are 'hot'; i.e. they are likely to have been accelerated in the conduction band of the diamond film by the penetrating field. On the other hand, these electrons have obviously suffered significant energy loss, as evidenced by the measured spectral shift from the Fermi level of the Mo substrate. In addition, the large spectral shifts, i.e. $\sim 2\text{--}3 \text{ eV}$, observed in this study indicate the existence of strong scattering mechanisms associated with the conduction electrons in the diamond film. However, the present result cannot provide information on the precise nature of the dominant scattering mechanism.

In summary, the spectral characteristics of electrons 'cold' emitted from diamond-coated Mo cathodes indicate, firstly, that electrons undergo extensive scattering during their transport through the diamond film, and secondly, that they are heated by the penetrating field prior to their emission into vacuum. It is therefore suggested that the emission mechanism involves the creation of electroformed conducting channels such as have been proposed to explain other dielectric switching phenomena. Finally, it is suggested that it is necessary to carry out further investigations aimed at identifying the dominant scattering mechanism.

This work was supported by the BMDO Office of Innovative Science and Technology through contract number N60921-91-C-0078 with the Naval Surface Warfare Center.

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