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THE PRACTICALITY OF HIGH MAGNIFICATION IMAGING BY POSITRON EMISSION

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ABSTRACT

The positron emission microscope has the capability of contrasting areas having high concentrations of monatomic vacancies and other defects. Since the positrons traveling through the specimen will have energies of the same magnitude as that of valence electrons, image contrast will be sensitive to the chemistry of the specimen. In the near future resolutions of 10 nm or lower will be achieved. Whether or not optical aberrations will permit one atom resolution is not clear. For one atom resolution to be obtained positron emission fluxes must be brightness enhanced to 10^{11} $sec^{-1}cm^{-2}$ or greater.

INTRODUCTION

The field emission microscope was investigated in the early stages of the development of electron microscopy (1). It was an attractive prospect because the optics are simple and the energy with which the electrons interact with the films on the surface of the emission needle are very low. The device has been of limited utility, however, because of the high electric fields necessary to extract electrons from inside the needle. The very high fields destroy adsorbed specimens and produce image artifacts. Electron emission microscopy has therefore failed to be of a utility comparable to that of transmission electron microscopy, in which high energy beams, typically 100 KeV, are projected through thin film specimens. Field ion emission microscopy has been quite useful, being capable of resolving individual atoms, but it has very limited application to specimens other than clean metal surfaces.

The advent of the brightness enhancement technique for positron beams, presents the possibility of a new of type low energy surface emission microscopy. Because the positrons are emitted spontaneously, due to the negative work function effect, the application of an external extraction field is unnecessary. Specimens should not be subject to breakdown, and image distortion should be less. Since the positrons emerge with energies of the same order of magnitude as that of valence electrons, we can expect the contrast of the image to be sensitive to the chemistry of the film through which they travel. If certain parts of the film have more tendencies to form positronium than the others, for example, the transmission through those parts should be lower. Another very attractive feature is the possibility to contrast areas having high concentrations of monatomic vacancies and other defects.

The authors pointed out the possibility of development of a positron emission microscope several years ago. Estimates of resolutions were presented (2). The recent successes of the Brandeis (3) and Michigan groups (4) in the experimental demonstration of the concept kindles renewed interest. Brandeis has reported real magnifications in excess of 1000 X (3). In this paper the authors speculate on what can be expected in the future.

EXPERIMENTAL REQUIREMENTS

Figure 1 is a sketch of the requirements of a positron emission microscope. Higher energy positrons, 2000-3000 eV, are focused onto the back of a thin film moderator. They become thermalized and diffuse to the front of the film, from which they are emitted and projected to an image onto a microchannel plate. The focusing optics are not indicated in Figure 1.

RESOLUTION EXPECTATIONS

To estimate the resolution capabilities of a positron emission microscope we will use the equation derived by Rose (5):

$$\delta = \left(\frac{2\hbar\tau}{mM}\right)^{1/2}\left[1 + \frac{2m\tau V^2}{\hbar M}\right]^{1/2}$$

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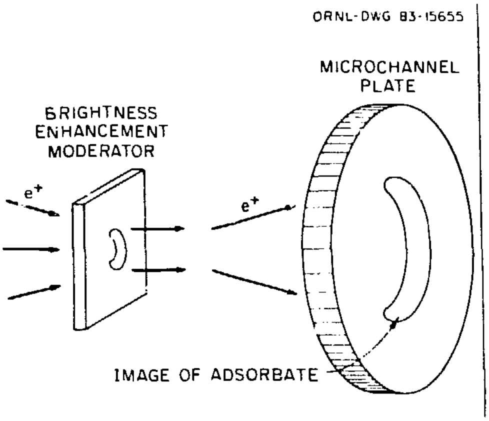

FIGURE 1

Schematic Diagram of Positron Emission Microscope

Where δ is the resolution, h is Plank's constant, τ is flight time from specimen to microchannel plate, v is lateral velocity of the positron as it leaves specimen surface, m is the mass of the positron, M is the geometric magnification of the projection optics. The term in parenthesis, on the right, arises from uncertainty principle considerations, the term in the brackets on the right takes into account resolution degradation due to lateral motion of the positron (or electron) as it leaves the surface. The Rose equation suggests that for magnifications lower than 500 KX the positron emission microscope might have a slightly better resolution than its electron counterpart. Positrons in moderators occupy the lowest possible band state, which allows them to assume thermal energies, thus traveling significantly slower than valence electrons, which are the particles extracted in field emission electron microscopes. For a magnification of 500 KX the resolution would be about 1.1 nm if the specimen is held at liquid nitrogen temperature. The lateral velocity term is essentially equal to unity for geometric magnifications greater than 500 KX, and it appears that the ultimate resolution of the positron microscope will be about the same as its electron counterpart. There will possibly be important differences in contrast capabilities between the two devices, however.

The geometric magnification, and therefore the resolution, of the positron emission microscope will be limited by the slow positron flux that can be achieved. For LINAC sources, this is typically 10^8 $sec^{-1}cm^{-2}$. Brightness enhancement might make it better by a factor of 10, but for the present we will assume this limit. If a flux of this magnitude is injected into the rear of a thin film moderator, the output from the front side might be as high as 10^7 $sec^{-1}cm^{-2}$. When this is projected to form an image, the magnification must be restricted to a sufficiently low level to maintain a flux greater than the noise level of the microchannel plate:

$$\frac{F}{M^2} > 4n$$

Where F is the flux coming from the surface of the film moderator, M is the geometric magnification, n is the noise level of the microchannel plate. For LINAC sources, positrons are delivered in 10-40 nsec pulses, each followed by a dead time of about 1 msec. Typical repetition rates are 1000 Hz. If the microchannel plate is deactivated during the dead times, and gated on for about 1 microsecond during the pulse delivery, it should be possible to reduce the noise level to about 10^{-3} $sec^{-1}cm^{-2}$. Thus the geometric magnification might be made as large as 50 KX, which would allow a resolution of about 10 nm for a specimen held at liquid nitrogen temperatures. In these calculations it is assumed that the acceleration voltage of the microscope is 50 KV, the flight path is 50 cm, flight time is 2.6 nsec.

According to the Rose equation, a geometric magnification of 10 MX will yield a resolution of 0.24 nm, which is approximately atomic size. It is questionable that this can be achieved. Bauer has considered more complicated factors, such as aperture abberations, in estimating the resolution of electron emission microscopes, and has concluded that 2 nm is the limit (5). To record an image having a geometric magnification of 10 MX the flux of positrons emitted from the specimen must be greater than 10^{11} $sec^{-1}cm^{-2}$.

CONCLUSIONS

It appears likely that, in the near future, positron emission microscopes having resolutions of 10 nm or smaller can be developed. Assuming the resolution of the human eye to be 0.2 mm, this corresponds to a real magnification of 20,000 X. Optical aberrations in the objective lenses available for positron emission microscopes might prohibit one-atom resolution from being achieved. To achieve one-atom resolution the positron emission beam must be brightness enhanced to a flux of 10^{11} $sec^{-1}cm^{-2}$ or greater.

Positron emission microscopes should have certain capabilities that electron microscopes do not have, such as the ability to contrast areas having high concentrations of monatomic vacancies and other defects. Contrast in the image should be sensitive to variations in the chemistry of the specimen.

ACKNOWLEDGEMENT

The authors extend their congratulations to the Brandeis and University of Michigan groups for having demonstrated that the positron emission microscope is a practical device. Their success will accelerate the progress of all of us who are interested in this subject.

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