25 K. Argon crystals have been grown on a clean Nb surface and it has been possible to get adequate diffraction patterns. If materials can be used where the surfaces can be cleaned at temperatures of, say 750°C, then Au–Fe thermocouples should provide an excellent way to measure the sample temperature. Also if smaller heating currents can be used, the thermal resistances from the sample to plug A and plate B can be made smaller and temperatures below 10 K can probably be attained with the apparatus described here. See Ref. 7 for a more recent discussion of this matter.

ACKNOWLEDGMENTS

We are grateful for discussions with F. Jona and J. E. Crow about some of the design features.

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* This work was done under the auspices of the U. S. Atomic Energy Commission.

† Now at Institute for Low Temperature Physics, Queens College of the City University of New York.

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[7] Since submission of this paper we have been able to obtain diffraction patterns of neon on niobium. Because the vapor pressure of neon is 10^{-9} Torr at 6.88 K and is up to 10^{-6} Torr at 8.5 K we estimate that our ambient temperature must below about 8 K. This means some of the estimates in our paper are somewhat conservative.

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 42, NUMBER 3 MARCH 1971

Metastable Atom Probe for Measurement of Electron Beam Density Profiles*

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(Received 21 September 1970)

A well collimated thermal beam of argon atoms, moving in the z direction, crosses the electron beam that is to be studied. Those argon atoms that are excited by impact to a metastable state proceed, with very little change in speed or direction, to a detector (windowless electron multiplier) some distance away. The neutral atomic beam of the metastable atom probe (MAP) has a negligible interaction with the electromagnetic fields that govern the behavior of the electron beam; moreover, almost no additional space charge is created when the atomic beam is introduced. Thus, if the cross section of the atomic argon beam is small compared to the characteristic dimensions of the electrode structure that defines the electron beam, the metastable atom count rate, monitored as a function of x and y, gives a virtually nonperturbative measurement of the density profile of the electron beam. In this paper we outline the principles and applications of the method, discuss details of its implementation, and give results obtained with an MAP that has a spatial resolution of better than 0.5 mm.

INTRODUCTION

THE electrodes for electron guns, photomultipliers, and other electron beam devices are often designed with the aid of computer models and with the use of electrolytic tank or rubber sheet analogs of trial electrode geometries.[1,2] These design studies may then be followed by the construction of a trial model (often scaled up from the envisioned final size) so that performance measurements can be made with current and field probes. The scaling and the probes themselves may introduce new factors into the electron beam characteristics. This design procedure is tedious and the results are often at variance with predictions. Thus there are obvious applications for new simple ways of examining electron beams that will operate on fairly compact electrode structures without introducing large perturbations.

In this paper we describe a method[3] for measuring electron current densities which depends on the electron impact excitation of neutral argon atoms to metastable states. The metastable atom probe (MAP) allows us to determine the current density in an electron beam as a function of two arbitrary coordinates with a spatial resolution better than 0.5 mm. The probe shows the effects of space charge, magnetic fields, and other factors which influence the electron current density, yet the MAP operates with such low atom beam densities (equivalent to less than 10^{-6} Torr in the center of the beam) that the perturbation introduced by the probe is very small indeed. Thus the MAP should be useful for the design of electron guns and electron beam devices of all kinds.

I. BASIC PRINCIPLES

The principles of the MAP are illustrated in Fig. 1. A rarefied, finely collimated beam of ground state argon atoms passes through the electron beam under study. A small fraction, perhaps one in a million, of the atoms will

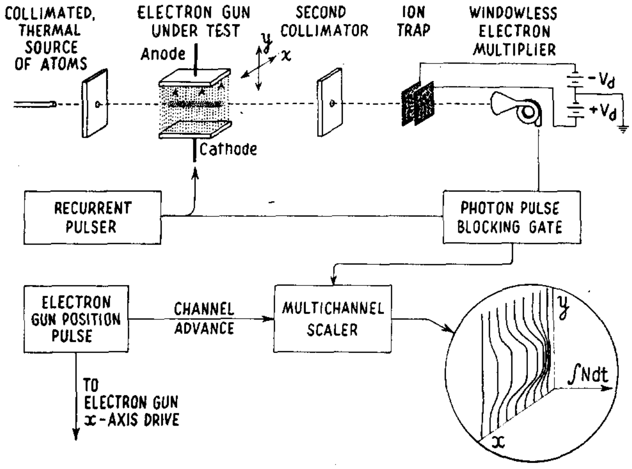

FIG. 1. Functional diagram of the metastable atom probe (MAP) as applied to the study of a simple diode.

interact with the electrons. The atoms that undergo elastic collisions, are ionized, or are excited to short lived ($\tau < 10^{-6}$ sec) excited states do not concern us directly; we are interested in those atoms that are excited to electrically neutral, metastable ($\tau > 10^{-2}$ sec) states. These metastable atoms, which suffer only a small change in speed or direction from the electron impact,[4,5] proceed with their characteristic thermal velocity ($\gtrsim 10^4$ cm/sec) to a distant, windowless electron multiplier where they are rapidly and efficiently detected.

The rate at which argon atoms are excited depends directly on the electron current density in the portion of the electron beam through which the argon atoms pass. Thus a spatial map of current density within the electron beam can be obtained by measuring the rate of production of metastable atoms as the argon beam is directed through different regions of the electron beam. The rate at which metastable atoms are detected, $N^*(x,y)$, is related to the electron current density $\rho_e(x,y,z)$ by

$$N^*(x,y) = KS(E)\int \rho_e(x,y,z)dz,$$

where the integration is over the effective length of the electron–atom interaction region. We assume that the cross section of the atomic beam is small compared to the significant x and y dimensions of the electron beam.

The first constant of proportionality, K, contains those factors, such as the flux of ground state atoms in the beam, the cathode emission, and the detector efficiency, that are assumed to remain constant during the time of the measurements. (Methods to overcome the effects of long term apparatus drifts are outlined in Sec. IV.)

The second factor of proportionality, S, contains the cross section for the electron impact excitation of atoms in the beam. S depends on the energy of the electrons, E. Argon atoms may be excited to their ${}^3P_2$ or ${}^3P_0$ metastable states provided that E exceeds the 11.55 and 11.72 eV excitation thresholds of these states. The cross section for production of metastable argon rises sharply at threshold and has an energy dependence that has been investigated in detail by Olmsted, Newton, and Street.[6] Thus, since the energy of an electron usually depends on its location within the electrode structure, and since S depends on electron energy, there will be an effective x, y dependence of S. If the electron beam is directed along y, however, there may be relatively little dependence of E on x, in which case a scan over x will yield a relatively good measure of the electron beam profile for a fixed y; x scans taken at different values of y can then be normalized to fair accuracy with the aid of the data shown in Fig. 4 of Ref. 6. We note that sensitivity curves for space charge limited electron guns have been presented by Locke and French.[5]

II. EXPERIMENT

In the present version of the MAP, the atomic beam source, the beam collimating plates, and the metastable atom detector are stationary; the electron gun to be studied is mounted on a movable stage, the position of which can be adjusted and measured from outside the vacuum envelope. The MAP requires a vacuum good enough so that the mean free path of the atoms is long compared to the source–detector distance; for our experiments we used a 700 liter/sec diffusion pump and a liquid

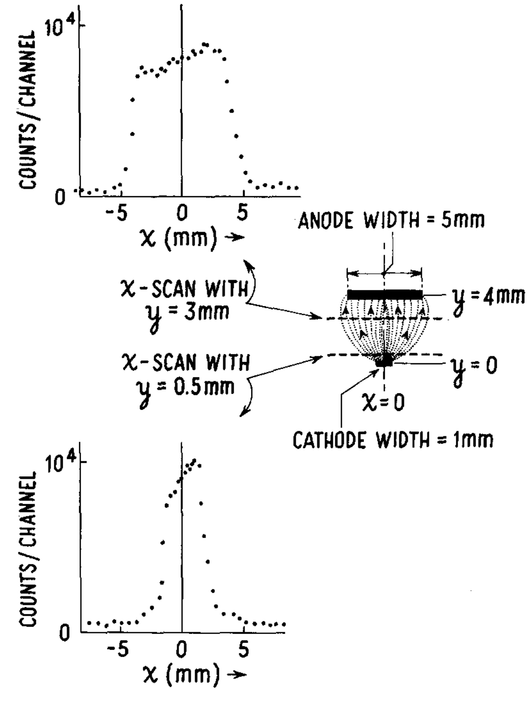

FIG. 2. Electron beam profiles at two different elevations within a diode. The cross section of the diode in the x–y plane is shown; both anode and cathode extended 2.2 cm in the z direction. Integration time for plots shown is 4 sec/channel.

nitrogen trap to keep the operating pressures well below 10^{-6} Torr. We have found that pumping the space between the gas source and the first collimator separately improves the signal-to-background ratio of the electron beam profiles.

During operation, industrial grade argon is fed into the gas source at about 10^{-2} μl/sec (we have found it important that the gas reservoir be filled with fresh argon before starting a day's run). Argon atoms emerge from the source in a rather broad divergent beam and travel to the first collimating plate where a narrow beam is defined by an 0.5 mm diam hole. This atomic beam then passes through the region of the electron gun that is selected by appropriate positioning of the gun with the movable stage.

Since the argon atoms are massive enough so that their velocities are changed only slightly[4] by the electron impact, the atomic beam, which now comprises both ground state and metastable atoms, continues through a small (1 mm diam) hole in a second metal plate and subsequently reaches the detector. This second plate further collimates the atomic beam to insure that only metastable atoms from the region of the electron beam under study reach the detector, and it also shields the detector from uv radiation from bare electron-gun filaments.

The metastable atoms are detected[7] with a windowless, continuous channel electron multiplier (Bendix Channeltron). The cathode of the Channeltron releases an Auger electron upon being struck by a metastable atom. The Auger electron initiates a cascade of electrons which emerges as the output pulse of the multiplier. The pulse, which is amplified and counted, is the signal of the arrival of a metastable atom. The multiplier is insensitive to ground state, thermal velocity atoms.

In addition to the excitation of the atoms to metastable states, excitation to short lived states as well as ionization also occurs. Ions and electrons, to which the detector is sensitive, are easily removed from the beam by suitably biasing the grids of an ion trap in front of the detector.

Ultraviolet photons, produced when the short lived states of the argon (and the residual gas atoms) decay, are also detected by the electron multiplier; these photons are a nuisance because they can easily swamp out the metastable atom signal. To prevent this it is convenient to run the electron gun in a pulsed mode rather than continuously: By driving the gun with 50 μsec pulses at a rate of 10^3/sec and by using a gate to admit to the scaler only those detector signals which come well after the end of the electron gun pulse, one can be certain that the large majority of the registered counts is from metastable atoms.

In a typical run, about 5 sec are spent at each x, y position and the counts arriving during this time interval are stored in a single channel of the scaler. In the present version of the MAP the y position of the beam is set manually; a stepping motor, correlated with the channel advance of a multichannel scaler, is used to sweep the x coordinate. The results given in Sec. III are from a single sweep over x for a given y setting. The electron beam density in the y–z plane is obtained by rotating the electron gun 90° about the y axis; it would be very useful to be able to do this without breaking vacuum.

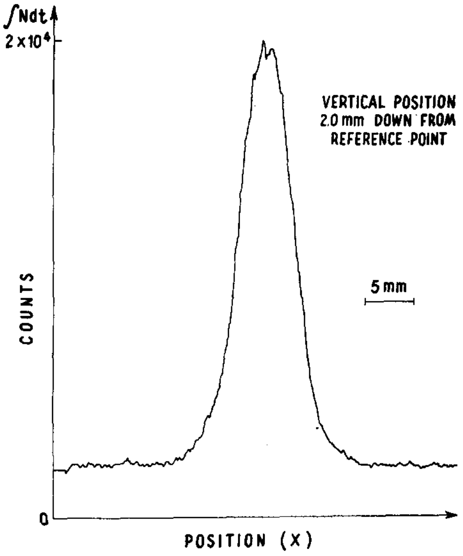

FIG. 3. Electron beam profile (as given by chart recorder driven by the multichannel scaler) for an electron beam completely enclosed in a 2 mm mesh wire cage. Integration time, 4 sec/channel. The y position is referred to the geometric center of the enclosure.

III. RESULTS

The metastable atom probe has been used to study a variety of electron guns. In Fig. 2 we show the electron density profile obtained at two different elevations within a simple diode. We note that the electron current distribution in this particular diode is not symmetric about the y axis; this is not an artifact of the MAP. Asymmetries can often be traced to distortions in the electric field caused by nearby support structures and to the stray magnetic fields from dc heated filaments.

When the anode of the configuration shown in Fig. 2 is narrowed from 5 to 0.4 mm, the density profile taken near the cathode is not significantly different from the $y=0.5$ mm scan shown in Fig. 2. The profile almost doubles in width when the scan is taken halfway between the anode and cathode, and it narrows again near the anode.

Figure 3 shows the profile of a beam of electrons that have been injected with an energy of 190 eV through a small (2.5 mm diam) hole into a wire mesh enclosure. The electron beam, as mapped with an atomic beam that goes in and out through the 2 mm mesh screening, spreads slightly after it enters the enclosure, but it is still quite well defined (Fig. 3) when it is 1 cm from the entrance hole. This electron beam has been used with the MAP apparatus for a verification of Snell's law for electrons.[8]

The density of the argon beam in the MAP apparatus is quite low, equivalent to a pressure of 10^{-6} Torr or less in the center of the beam. Thus these electron guns, which have peak electron currents on the order of 10^{-3} A, have less than 10^{-8} A of positive ion current that arises from the presence of the MAP beam.

IV. DISCUSSION

The resolution of the present instrument is sufficient to show significant changes in electron beam densities over separations as small as 0.5 mm. This spatial resolution can be improved by collimating the beam more finely and by taking steps to minimize the spread of the beam caused by recoil from electron impact.

The collimation of the present MAP beam yields an effective probe diameter of about 1 mm. The collimator holes could be made considerably smaller to reduce this diameter, down to a size where the count rates from the metastable atoms become comparable to the noise level of the detector. The limits on collimation depend to a considerable extent on the electron current density within the gun and on the integration times one is willing to employ.

The beam spreading caused by the impact of electrons on the ground state atoms depends inversely on the velocity and mass of the atoms. Thus one can improve the spatial resolution by using a gate so that only the signals from the fastest of the argon atoms are registered in the scaler. One can also employ heavier atoms for the beam; both krypton (mass$\simeq$83 amu) and xenon (mass$\simeq$130 amu) are suitable; however, they are far more expensive than argon. Since the heavy noble gases all have different metastable state excitation thresholds ($\simeq$11.6 eV for argon, $\simeq$9.9 eV for krypton, $\simeq$8.3 eV for xenon), MAP studies of the same electron gun with all three gases may give useful information on the distribution of electron energies within the gun.

It would be advantageous to couple both the x and y drives of the MAP to position-to-amplitude encoders and to use a pulse height analyzer for data acquisition. In this way one would be able to integrate the MAP profiles over many rapid scans over x and y in order to average out the effects of long term fluctuations in the atomic beam flux and in the cathode emission. Moreover one could have an oscillographic, isometric display[9] of the entire set of x–y scans by using a two-parameter analyzer of the sort that is common in nuclear physics laboratories.

ACKNOWLEDGMENTS

We are particularly grateful to Russell Pichlik for his help with the early phases of this work. We thank J. Thomas Dickinson for permission to use the data of Fig. 3 prior to publication. We thank John Pearl, Denis Donnelly, and Richard Heppner for their friendly support. We are indebted to Professor Raulf Polichar for the loan of apparatus.

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[*] Research supported in part by the National Aeronautics and Space Administration and by the U. S. Atomic Energy Commission.

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