

FIELD EMISSION SPECTROMETER WITH AN ELECTRON MULTIPLIER OPERATING IN THE PHASE-SENSITIVE DETECTION SYSTEM

BY C. J. WORKOWSKI AND J. J. CZYŻEWSKI

Institute of Experimental Physics, University of Wrocław*

(Received November 21, 1970)

An improved field emission spectrometer is described. A hemispherical grid is used in the place of the collector of electrons in the van Oostrom type analyzer. This design permits an electron multiplier to be used. To obtain a high gain stability, a Lallemand type multiplier has been constructed for this purpose. It has good vacuum properties as well. Energy distributions of field-emitted electrons are obtained directly on an xy recorder by the use of modulation and phase-sensitive detection. The modulation frequency is 225 Hz. The use of a Cardan suspension of the tip enables measurements for any desired crystallographic direction of the emitter to be made. By submerging the spectrometer tube in liquid nitrogen, a vacuum in the 10^{-11} torr range is easily reached. The energy spectra of field-emitted electrons for the $\langle 001 \rangle$, $\langle 012 \rangle$ and $\langle 112 \rangle$ directions of a tungsten monocrystal have been measured. The performance of the spectrometer is illustrated by the quality of these measurements. It is shown that the utilization of a hemispherical grid does not preclude the achievement of a high resolution.

1. Introduction

Since Müller invented the retarding potential spherical analyzer for measurement of energy distributions of field-emitted electrons (Müller 1936), this device has undergone some evolution (Young and Müller 1959, Russell 1962, Mileshkina and Sokolskaya 1963, van Oostrom 1966). Recently, a high resolution of order 10^5 (or 10 meV in the absolute energy scale) was reached. All field-emission spectrometers known to the authors were based on the retarding potential idea.

One can distinguish, in general, three parts in the spectrometer tube (Fig. 1): (i) the emitter arrangement for varying the crystallographic direction, along which the emission is studied, (ii) the system of analyzer electrodes, and (iii) the emission current measuring system. We shall be especially interested in the third part.

In Young-Müller's (1959) and Mileshkina-Sokolskaya's (1963) tubes the spherical retarding electrode was simultaneously a collector, and the collector current was measured directly by means of an electrometer. Electron energy distributions were obtained by graphical differentiation of retarding potential measurements. The electrode system was constructed

* Address: Instytut Fizyki Doświadczalnej Uniw. Wrocławskiego, Wrocław, Cybulskiego 36, Poland.

in such a way that the collector saw the whole anode. This caused the instabilities and noise from high-voltage anode circuit to be transmitted to the electrometer input throughout the anode-collector capacitance. Also, the secondary emission of the collector could falsify the measurements. These effects can be removed by separating the current measurement

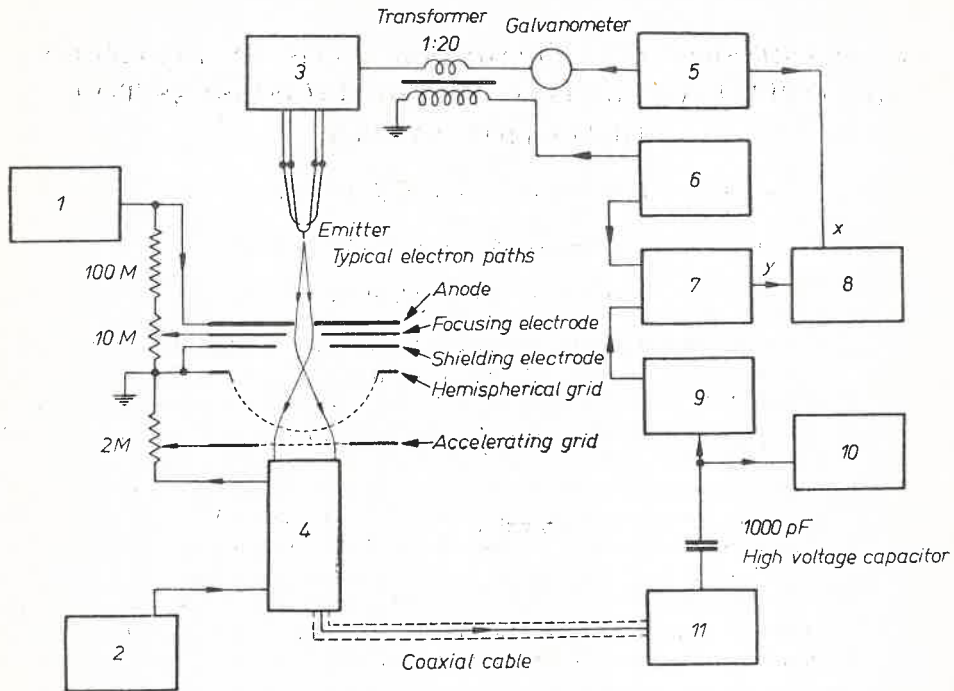


Fig. 1. Block diagram of the field emission spectrometer. 1-2 — high voltage supply, 3 — emitter temperature controller, 4 — electron multiplier, 5 — emitter bias, 6 — generator, 7 — homodyne rectifying voltmeter, 8 — recorder, 9 — selective microvoltmeter, 10 — CRO, 11 — preamplifier

system (iii) from the influence of the anode electric field. It was Russell (1962) who fulfilled the above condition by adding a Faraday cage behind the hole in the spherical retarding electrode. Besides, it makes possible the collector to be fully shielded, what is important when the precise measurement is accomplished by means of a very high input impedance electrometer operating in the phase sensitive detection system. The total energy distribution was obtained by electrical differentiation. The resolution was, however, considerably lower than for other spectrometers. Van Oostrom (1966) has recently constructed an analyzer with the better resolution and limited influence of the anode electric field on the current measurement system. His tube, however, was not equipped with a circuit for the electrical differentiation of retarding potential measurements. It is advantageous to utilize an electron multiplier in the field emission spectrometer. This permits the sensitivity of a system to be improved considerably and the use of the electrical differentiation becomes easier. Such a spectrometer of a high resolution has been constructed and the aim of this paper is to give the description of this instrument.

2. Design of the experimental tube

In our spectrometer (Fig. 2) the geometry of the analyzer electrodes is similar to that used by van Oostrom (1966). However, the principal virtue of our design is that there are considerable innovations and changes in the experimental tube and circuits. One can mention here: (j) the utilization of a Cardan suspension of the tip, (jj) the replacement of the

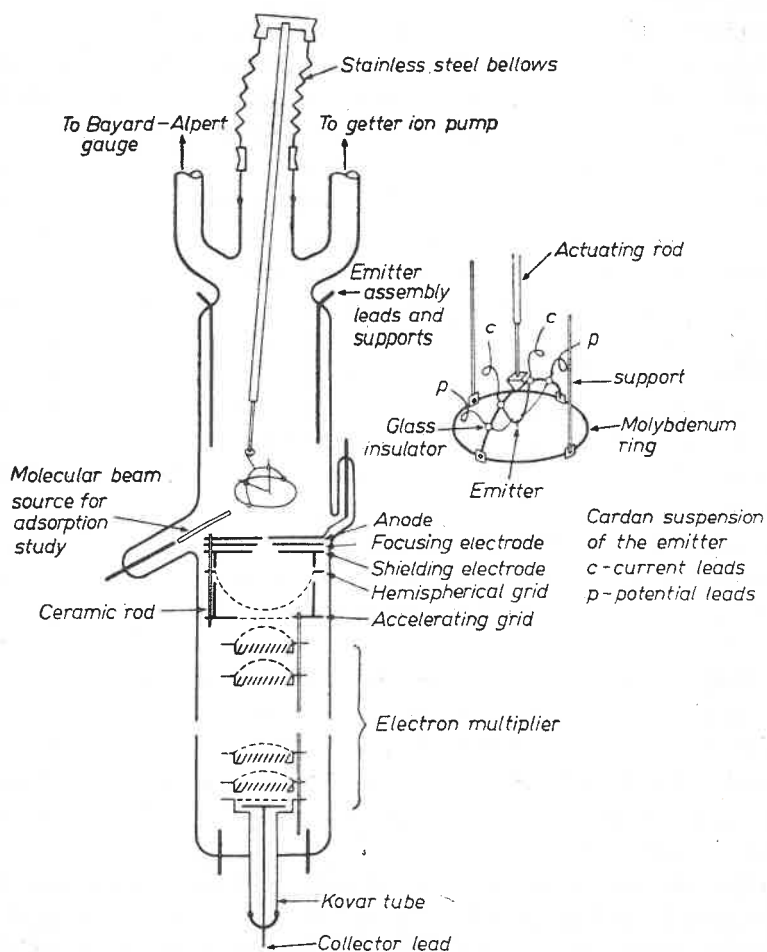


Fig. 2. Schematic representation of the retarding potential tube

hemispherical collector with a hemispherical grid in order to be able to use an electron multiplier, (jjj) small changes in the geometry of the analyzer, such as a smaller diameter of the probe hole and (jjjj) the phase-sensitive detection system operating together with the electron multiplier. Each point will be described in detail.

Some doubts concerning the tube with magnetic deflection, confirmed by Swanson's and Crouser's (1967) measurements, disposed us to use the mechanical arrangement (Fig. 2)

for varying the direction of the emitter axis with respect to the electron-optical axis of the analyzer. The tip was mounted on the Cardan suspension in such a way that it could be rotated about its center (Schmidt and Gomer 1966). The deflection angle could be varied within the range of $\pm 45^\circ$. Desired rotation could be obtained from outside by means of an actuating rod, attached to a stainless-steel bellows (Fig. 2). Therefore, the angle between the probed electron beam and the analyzer axis was kept constant when the crystallographic direction was varied.

The graphical differentiation method of the retarding potential measurement is very laborious, inexact, and limits the measurement efficiency. But electric differentiation requires an electrometer having a time constant of the input circuit as low as 10^{-3} s. Moreover, there are difficulties in shielding this system, in particular, when experimental tube is immersed into liquid nitrogen and bubbling of nitrogen raises the noise level. These obstacles can be evaded by using another device of the analyzer. Namely, in our spectrometer the hemispherical grid was employed in the place of the hemispherical collector (Fig. 2). Thereby, the spherical geometry of the retarding field was maintained and the beam of electrons of energy higher than the retarding potential could be led out of the analyzer. The electrons after passing through the grid were directed towards the electron multiplier.

The grid was made of 100 lines/cm nichrom etched mesh with about 70% transmission. Its radius of curvature was 24 mm. Apertures in the analyzer electrodes decreased towards the emitter; they were, respectively, 0.7, 1.4, and 2.8 mm. Once both the grid and the multiplier were used, a low value of input time constant (10^{-3} s) of the phase-sensitive detection system was easily obtained.

In our application the electron multiplier had to fulfil some particular conditions. The coefficient of current amplification should be constant throughout the measurement. Moreover, the presence of the working electron multiplier in the tube should not enhance the pressure above the value of 1×10^{-10} torr. For this reason an electron multiplier of the Lallemand (1949) type was used. Therefore, the possibility of an electrostatic action on the multiplier amplification stability of insulators being charged by secondary emission was eliminated. Dynodes were made of CuBe alloy, and they were activated in oxygen atmosphere (Yoshida *et al.* 1953). Focusing grids had about 85% transmission. The resistors of the voltage divider were mounted inside the tube. No changes of electron multiplier gain was noted during several months of operation.

Tube electrodes were made of such materials as nickel molybdenum and nichrom. This last was used for making the grids. The metallic and ceramic mounting of the analyzer and multiplier permitted the use of rf heating for outgassing. Before sealoff the tube was evacuated and baked by the typical procedure. During the operation the entire tube was submerged in liquid nitrogen, enabling easy access to a vacuum in the 10^{-11} torr range.

3. Automatic differentiating system

The well-known idea of electrical differentiation of retarding potential measurements (Russell 1962, Leder and Simpson 1958) is based on the fact that if a sufficiently small ac signal is superimposed on the retarding potential, the first derivative of retarding measure-

ments is proportional to the ac component of the collector current. Thus, electron energy distributions are directly obtained by recording the relationship of the ac component of collector current to the retarding potential. Figure 1 shows a circuit realizing this idea as well. The description of our circuit is limited only to specific details because the general principles are published in the literature (Russell 1962, Leder and Simpson 1958, Nathan and Mee 1967, Spicer and Berglund 1964).

A multiplier output was connected with a dc preamplifier by a 1.5 m doubly shielded cable. Both the internal shield and the preamplifier were at the multiplier anode potential. Therefore a long cable is necessary for operating the tube in a cryostat.

It is advantageous to measure the energy distribution of field-emitted electrons for a small total emission current of about 1×10^{-7} A. Thus, the output analyzer current is expected to vary between 10^{-11} and 10^{-15} amperes. To obtain a reasonable output ac multiplier signal for a multiplier gain of 10^4 , the anode resistor had to be 5×10^7 ohms for maximum sensitivity of the system. This resistor, which can be varied from 1×10^6 ohms to 5×10^7 ohms is at the same time the preamplifier grid resistor. By using the feedback circuit described by Pelchowich and van Zelst (1952) a reduction of the time constant resulting from both the cable capacitance and the grid resistor was obtained. The magnitudes of both this time constant and the noise of the anode multiplier circuit determine the sensitivity of entire system. A carefully shielded multiplier output considerably reduces the noise. The main source of 50 and 100 Hz noise was the HV supply of the electron multiplier. Therefore, special efforts were made to decrease the ripples and fluctuations of this supply. The preamplifier gain was 50 when the feedback circuit was opened. The battery-supplied preamplifier was assembled in an equipotential box operating at high potential. Circuits after the preamplifier were isolated from the high voltage by a 1000 pF capacitor. After amplification by the preamplifier, the ac signal passed a selective microvoltmeter (UNIPAN type 227) of 50 dB octave selectivity and then a homodyne rectifier voltmeter (UNIPAN type 202B). This last was driven by a reference signal obtained from the same oscillator which supplied the modulation signal to the emitter. Finally, the output of the homodyne rectifier voltmeter was coupled down to an *xy* recorder. The magnitude of the ac signal was plotted on this *xy* recorder as a function of the retarding voltage. The retarding (bias) potential supply contained a precision potentiometer for fine regulation. The hemispherical grid was kept of the ground potential. The entire apparatus is illustrated by the block diagram in figure 1.

4. Performance

The performance of the system is illustrated in figure 3. The curves in figure 3 show that the value of the energy width at half-height of the energy distribution for the $\langle 112 \rangle$ and $\langle 012 \rangle$ directions of the tungsten monocrystal are nearly equal to the theoretical value based on the free-electron model (Young 1959, van Oostrom 1966). This indicates that the utilization of hemispherical grid in the place of collector is not an obstacle in obtaining high resolution. Besides, use of the grid eliminates the error in the retarding potential caused by the voltage drop across the input resistor of the electrometer, which is usually not taken into account. The values of the energy width at half-height obtained in the present

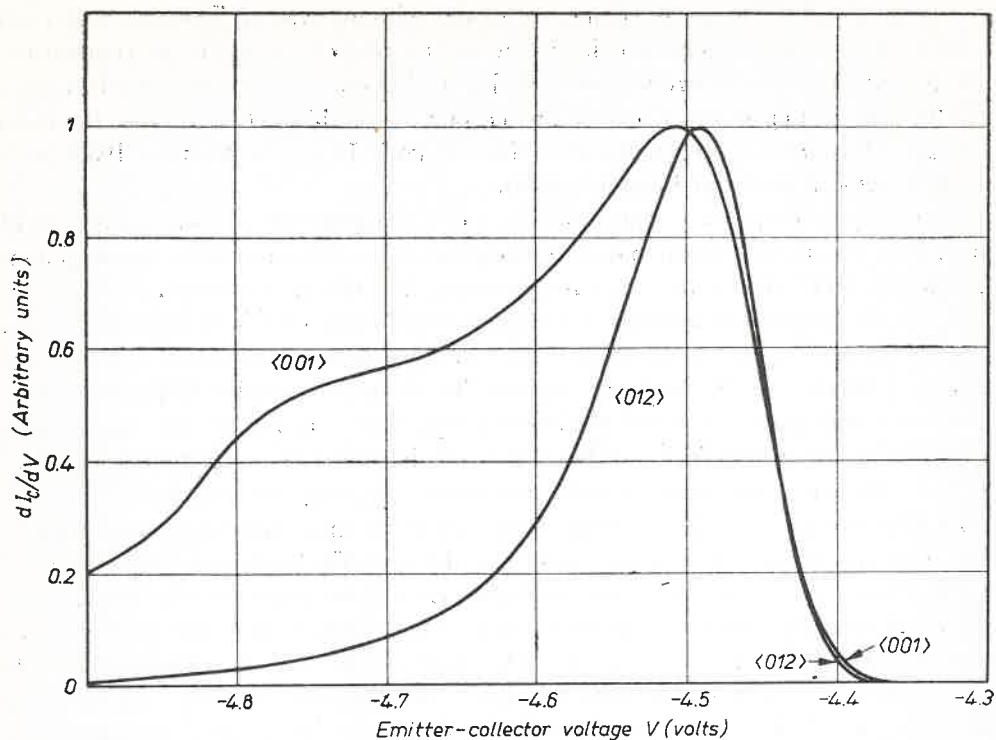


Fig. 3. Total energy distributions of field-emitted electrons for various crystallographic directions of tungsten emitter at the temperature of 78°K. Curves for $\langle 112 \rangle$ and $\langle 012 \rangle$ are identical. dI_c/dV is collector current derivative arbitrarily normalized

The half-height width σ of the energy distribution curve for thermally annealed tungsten (measured at 78°K)

References	$\sigma_{\langle 114 \rangle}$	$\sigma_{\langle 112 \rangle}$	$\sigma_{\langle 001 \rangle}$
Young and Müller (1959)	160 meV*		
van Oostrom (1966)	136 meV		
Swanson and Crouser (1967)		193 meV	393 meV
Present work		119 meV	322 meV

* Corrected result for region with work function of 4.4 eV but without detailed specification of crystallographic direction.

work and those of other authors are listed in table. They can be regarded as a measure of reached resolution.

The anomalies for the $\langle 100 \rangle$ direction shown in figure 3 confirm the results of Swanson and Crouser (1967) even though a $\langle 110 \rangle$ oriented emitter was used. The quality of this spectrum illustrates the performance of present system as well.

The authors would like to thank Docent Z. Sidorski for his kind interest he has shown in this work.

REFERENCES

- Lallemand, A., *Le Vide*, **21**, 618 (1949).
Leder, L. B., Simpson, J. A., *Rev. Sci. Instrum.*, **29**, 571 (1958).
Mileshkina, N. V., Sokolskaya, I. L., *Fiz. Tverdogo Tela*, **5**, 2501 (1963).
Müller, E. W., *Z. Phys.*, **102**, 734 (1936).
Nathan, R., Mee, C.H.B., *Rev. Sci. Instrum.*, **38**, 1785 (1967).
Pelchowich, I., van Zelst, Z. J. J., *Rev. Sci. Instrum.*, **23**, 73 (1952).
Russel, A. M., *Rev. Sci. Instrum.*, **33**, 1324 (1962).
Schmidt, L. D., Gomer, R., *J. Chem. Phys.*, **45**, 1605 (1966).
Spicer, W. E., Berglund, C. N., *Rev. Sci. Instrum.*, **35**, 1665 (1964).
Swanson, L. W., Crouser, L. C., *Phys. Rev.*, **163**, 622 (1967).
van Oostrom, A. G. J., *Philips Res. Reports Suppl.*, **1**, 1 (1966).
Yoshida, S., Takeda, I., Igarashi, Y., Arata, H., *J. Phys. Soc. Japan*, **8**, 318 (1953).
Young, R. D., Müller, E. W., *Phys. Rev.*, **113**, 115 (1959).
Young, R. D., *Phys. Rev.*, **113**, 110 (1959).