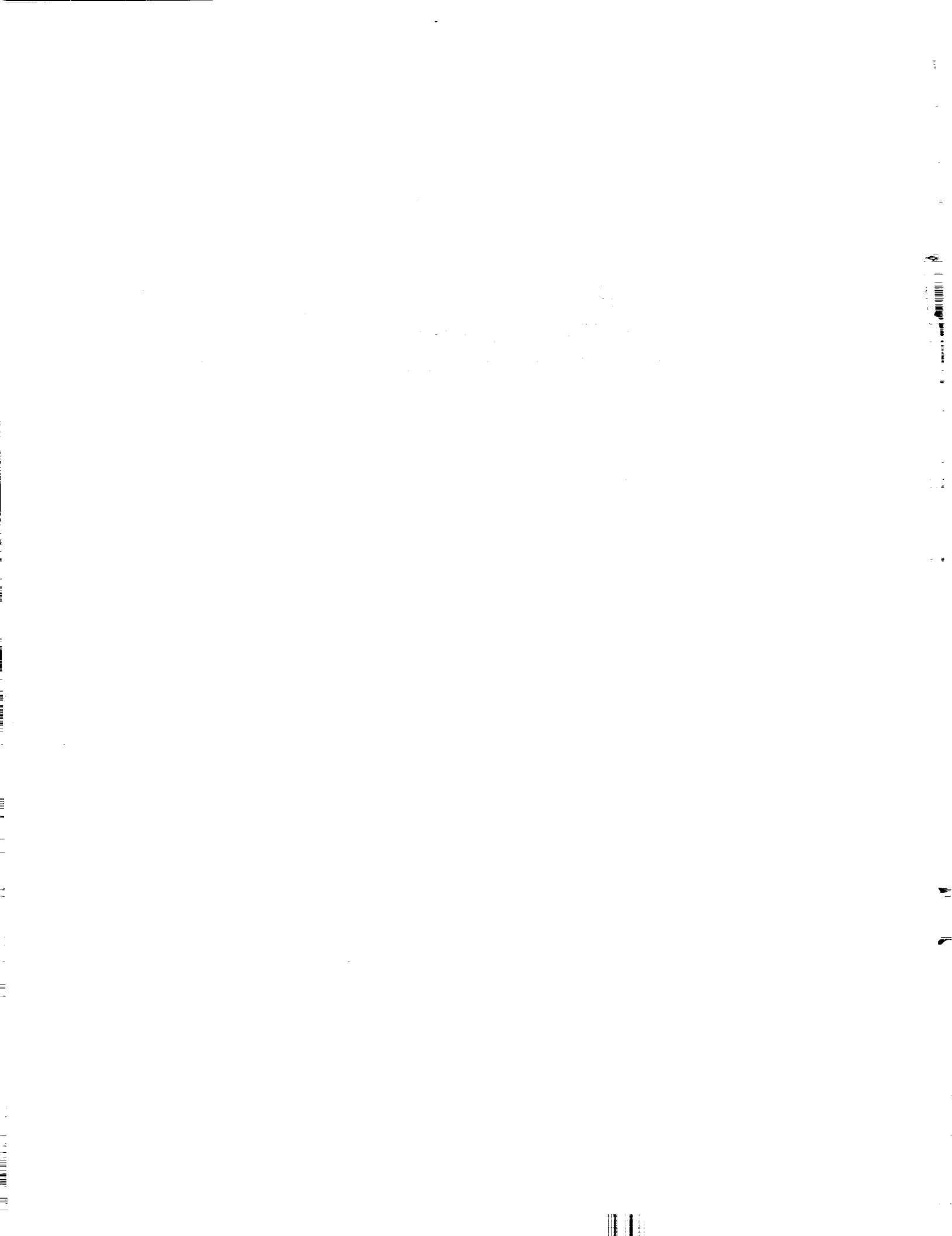**NASA
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Secondary Electron Emission Characteristics of Molybdenum-Masked, Ion-Textured OFHC Copper

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Summary

A method for producing a uniform, highly textured surface on oxygen-free, high-conductivity (OFHC) copper by ion bombardment using sputtered molybdenum as a texture-inducing masking film was developed and used to provide samples for study. The purpose was to develop a basically OFHC copper surface having very low secondary electron emission characteristics. Surfaces having low secondary electron emission are a requirement for the electrodes of very high efficiency multistage depressed collectors (MDC's). Such MDC's are used in microwave amplifier traveling-wave tubes for space communications and other applications. OFHC copper is the material most commonly used for MDC electrodes because it has high thermal conductivity, it is easy to machine, and its fabrication and brazing procedures are well-established. However, its untreated surface displays relatively very high levels of secondary electron emission.

Textured OFHC copper samples were tested for true secondary electron emission and relative reflected primary electron yield at primary electron beam energy levels from 200 to 2000 eV and at direct (0°) to oblique (60°) beam impingement angles. The test results for three of the samples, each of which was processed in a slightly different way, are compared with each other and with test results for a machined OFHC copper sample. Although the textured samples are not represented here as having been processed optimally, their measured secondary electron emission characteristics are significantly lower than those of the untreated OFHC copper sample over the range of conditions studied. Importantly, the relative reflected primary electron yield of one of the textured samples is conspicuously lower than that of the others. Clearly, with further development, the molybdenum-masked, ion-textured OFHC copper surface will be a promising material for high-efficiency MDC electrodes.

Introduction

Developing technology to improve the efficiency, reliability, and signal quality of microwave amplifier tubes (TWT's) is an ongoing effort at the NASA Lewis Research Center. A major contribution to this technology was the invention and development of the multistage depressed collector (MDC) (ref. 1), in which the entering spent electron beam is slowed by a retarding electrical field and the electrons are collected selectively by electron energies with relatively small losses. To attain the highest collector efficiency, the MDC electrodes must have low secondary electron emission characteristics so that the electrons are not excessively re-emitted or reflected from the surfaces (ref. 2.).

The material most commonly used for MDC electrodes is oxygen-free, high-conductivity (OFHC) copper. Although this metal has high thermal conductivity, is easy to machine, and its fabrication and brazing procedures have been well-developed, its untreated surface has relatively high secondary electron emission characteristics. Some topical treatments such as sputter-applied titanium carbide have been used on OFHC copper to moderately reduce the emission characteristics (ref. 3). A more effective way to reduce the emission properties of OFHC copper is to modify the surface by means of ion texturing. Subjecting OFHC copper to ion bombardment under the proper conditions yields a highly textured surface that displays markedly lower secondary electron emission characteristics than does the untreated surface.

Reference 4 describes the characteristics of OFHC copper which has been ion-textured with a texture-inducing "seed" or "mask" of tantalum. Although that surface displays promisingly low secondary electron emission characteristics, a very small amount of residual tantalum remains on the textured surface, as indicated by Auger spectrographic examination. That small amount of tantalum is generally viewed as being incompatible with subsequent MDC assembly procedures that would involve furnace brazing in other than a vacuum environment. In response to that restriction, a procedure for ion-texturing OFHC copper which uses molybdenum as the masking material was developed and is the subject of this study. Although small amounts of molybdenum also remain on the ion-textured surfaces studied, the molybdenum is compatible with conventional vacuum-brazing procedures if such are required (ref. 5). The use of this surface may be particularly attractive to MDC manufacturers who use OFHC copper electrodes, since it has the potential of increasing collector efficiency without significantly changing basic design, fabrication, or TWT processing procedures. For this reason, the molybdenum-masked, ion-textured OFHC copper surface should be considered to be a promising candidate MDC electrode material, even though its secondary electron emission characteristics are not at the lower levels of ion-textured graphite and carbon and carbon-coated surfaces reported in other studies (refs. 6 and 7).

The objective of this study is to describe the molybdenum-masked, ion-textured OFHC copper surfaces studied and the procedures used to produce them, as well as to report the secondary electron emission characteristics of these surfaces over a range of primary electron beam energies and beam impingement angles representative of MDC electrode application. A summary of these characteristics for untreated OFHC copper is presented for comparison.

Experimental Apparatus, Materials, and Procedures

Ion Texturing

A schematic of the ion-texturing facility used in this study is shown in figure 1. A detailed description of this apparatus and its operating procedures is presented in reference 8. Briefly, a sample of the material to be treated was positioned in the instrumented receptacle structure shown in the schematic and was subjected to ion bombardment in a low-pressure $(3.99 \times 10^{-3}$

to 5.32×10^{-3} Pa; 3×10^{-5} to 4×10^{-5} torr) environment. Operating variables in the procedure were accelerating potential difference between the cathode and the sample, argon flow rate, sample surface current density, and duration of ion bombardment. The OFHC copper samples textured in this study were disks approximately 2.1 cm (0.828 in.) in diameter by 0.15 cm (0.060 in.) thick. The samples were cleaned immediately before texturing by successively washing them in clean acetone (minimum 99.7-percent pure), clean ethyl alcohol (minimum 94.9-percent pure), and clean double-distilled, demineralized water; then the samples were air-dried.

Figure 2 is a photograph of the sample receptacle, which is shown in place schematically in figure 1. Mounted above and surrounding the sample was a narrow pure-molybdenum skirt that sloped inward toward the sample at a 45° angle. The inside diameter of the 0.635-cm (0.25-in.) wide skirt was about 4.53 cm (1.785 in.), and the height of the skirt above the level of the sample surface was about 0.795 cm (0.313 in.). The molybdenum skirt provided a sputtered "seed" or "mask" for the OFHC copper sample surface. A material such as molybdenum (which has a higher melting temperature than
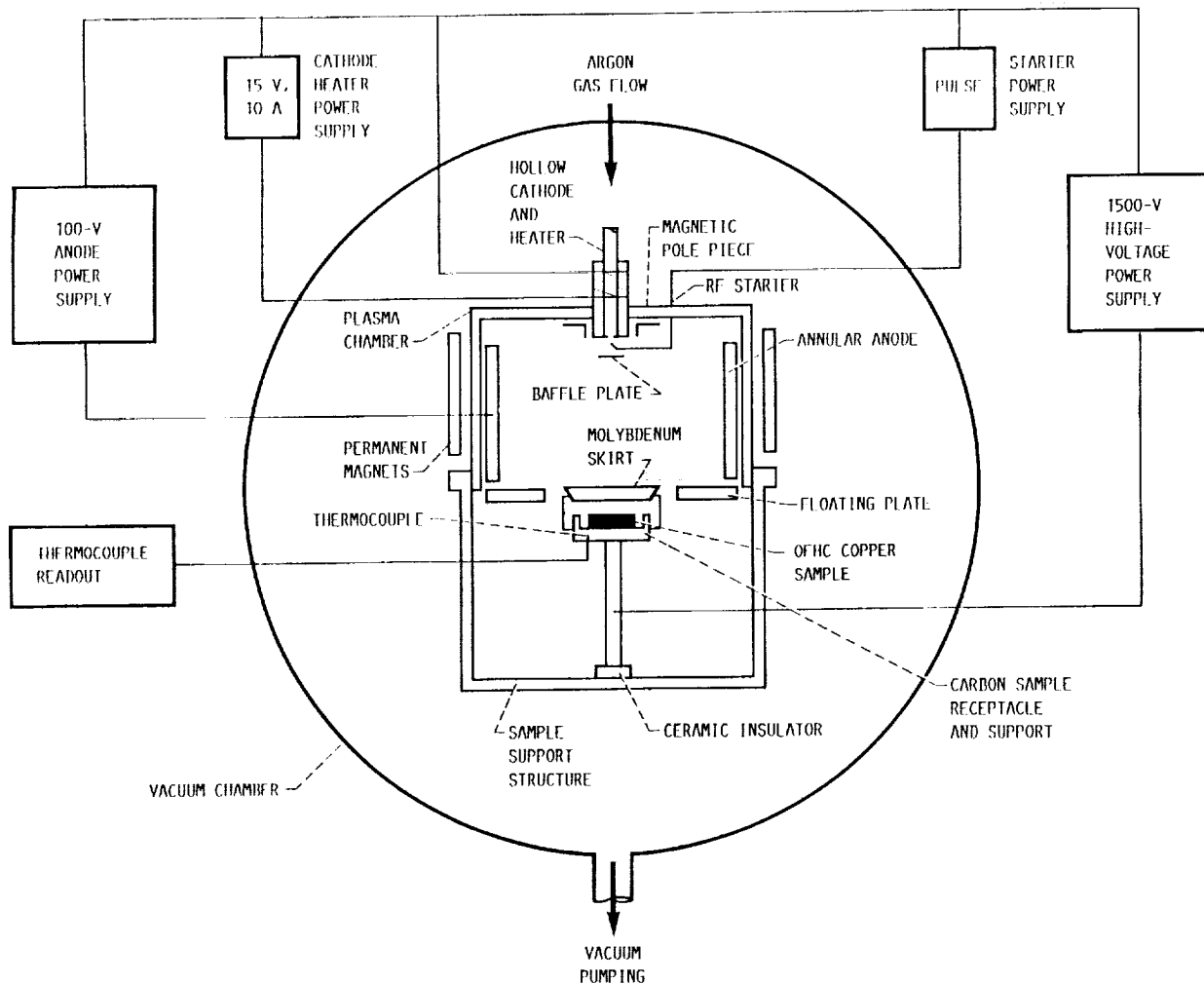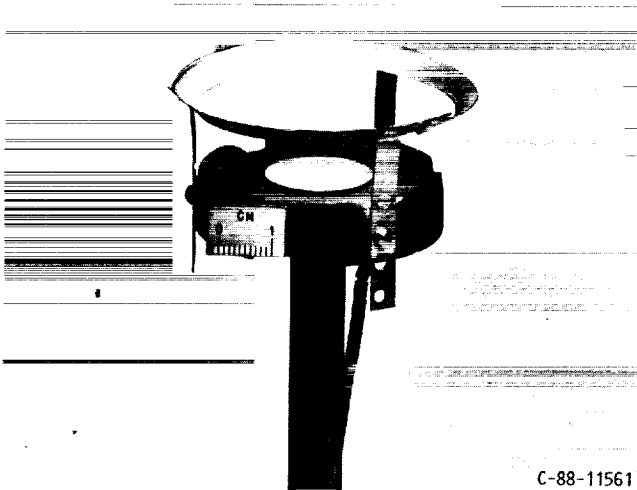

Figure 1.—Schematic of ion-texturing apparatus.

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Figure 2.—Sample receptacle and support structure showing OFHC copper sample in position prior to installation in ion-texturing apparatus. (Note molybdenum skirt surrounding sample and supported by molybdenum risers. Also visible in the photograph is a pair of insulated thermocouple lead wires.)

OFHC copper), when arranged and electrically biased properly, "seeds" the OFHC copper surface and causes texturing to occur under ion bombardment. Specifically, for all of the OFHC copper samples ion textured in this study, the accelerating potential difference was 1500 eV, and the argon flow rate was 70 to 75 std cm^3/min. The texturing periods for the three OFHC copper samples included in this study were 2.0, 1.0, and 1.5 hr for samples 1, 2, and 3, respectively. The corresponding surface current densities for the three samples, were 5, 6, and 6 mA/cm^2, respectively. During the entire period of ion bombardment, the skirt and samples were held at the same potential relative to the cathode. Proper placement of the seeding material is important for producing uniform and mature texturing over the surface configuration to be treated. Depending on the complexity of the surface to be treated, some experimentation with seed material placement and operating procedures may be required to produce uniform and effective texturing over the entire surface.

The fabrication of the molybdenum skirt and its supports required some special procedures. The skirt used in this study was 0.038 cm (0.015 in.) thick and was mandrel formed to the shape shown in figure 2. Since molybdenum does not bond well to itself when spot-welded, a thin (0.0127 cm; 0.005 in.) piece of 304 stainless steel was "sandwiched" between the overlapping ends of the molybdenum skirt and also between the skirt and the ends of the supporting vertical molybdenum legs. Care was taken to conceal the small stainless steel pieces from the plasma environment to prevent them from parti-cipating in the sputtering process. First, sharpened copper welding points were used to spot weld the stainless steel pieces at low energy (40 to 50 W-sec) to one molybdenum side of the joint, and then the entire "sandwich" was welded at higher energy (about 150 W-sec) by using a conventional spot-welder. Skirts fabricated in this manner could be used for several hours

in the ion-texturing process before material depletion would result in loss of dimensional integrity and exposure of the stainless steel bonding material.

Materials Investigated

As was stated in another section of this paper, OFHC copper is the material most commonly used for MDC electrodes, principally because of its relatively high thermal and electrical conductivity and its well-established fabrication and brazing procedures. The relatively high secondary electron emission properties of its untreated surface, however, make it a rather poor material for electrodes for high-efficiency MDC's. This study describes a method for significantly reducing the secondary electron emission of OFHC copper by subjecting it to ion bombardment to produce a highly textured surface. This was accomplished by sputter applying a texture-inducing "seed" or "mask" of arc-cast molybdenum to the OFHC copper surface during the period of ion bombardment. Molybdenum was selected for this procedure because it satisfies the requirement for the target material to have a higher melting temperature than the OFHC copper substrate material (indicated in ref. 9), and because it is compatible with conventional furnace-brazing procedures commonly used with MDC and TWT fabrication.

Table I presents some selected properties (taken from ref. 5) of the materials used in this study. The melting temperature of molybdenum is, of course, much higher than that of OFHC copper, satisfying the seed material requirement. Although the densities of the OFHC copper and molybdenum are similar, a significant difference in the coefficients of thermal expansion is apparent. Since material applied by sputter deposition typically displays excellent adhesion, detachment of the molybdenum from the textured OFHC copper surface because of thermal cycling in actual MDC electrode application is not perceived as a problem. Even though the amount of molybdenum remaining on the textured surface is expected to be very small and to pose no significant problems in electrode operation, nevertheless molybdenum removal from the textured surface by selective sputtering or other means may be a desirable goal for subsequent investigation.

TABLE I.—SOME SELECTED PROPERTIES OF OXYGEN-FREE, HIGH-CONDUCTIVITY (OFHC) COPPER AND ARC-CAST MOLYBDENUM

Property	OFHC copper (99.3 wt % minimum)	Arc-cast molybdenum (99. 9 wt % minimum)
Density at room temperature, g/cm$_3$	8.94	10.2
Melting temperature, °C	1083	2620 ± 10
Coefficient of thermal expansion at room temperature, cm/cm/°C	16.5 × 10^{-6}	5.1 × 10^{-6}

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Secondary Electron Emission Evaluation

The facilities and procedures used to evaluate the secondary electron emission characteristics of the untreated and molybdenum-masked, ion-textured OFHC copper samples investigated in this study are described in detail in reference 8. Briefly, the samples were attached to a micromanipulator-mounted support fixture and installed in an ultra-high-vacuum vessel equipped with a scanning Auger cylindrical mirror analyzer (CMA) that had an integral electron gun. The vessel also had a residual gas analyzer (RGA). A filament heater-reflector system and a thermocouple were incorporated into the sample-holding fixture for sample degassing and temperature monitoring. The vacuum chamber was evacuated prior to testing to a pressure of 399 nPa (3×10^{-9} torr) or less as indicated by the triode ion pump control unit panel meter. During the pumpdown the entire vacuum chamber was heated to about 250 °C for 16 hr to degas the system. After that procedure the samples were heated by filament radiation and electron bombardment to about 500 °C for 3 to 4 hr to further degas the sample and to simulate the anticipated "bakeout" temperature to which an MDC assembly on a TWT would be subjected. Along with the secondary electron emission measurements, Auger spectroscopic examinations were conducted to determine the elemental compositions of the sample surfaces. These examinations and measurements are discussed in the section "Experimental Results."

The bottom half of each sample disk was coated with soot to provide a control surface. This half of the ion-textured sample was smoothed by abrasion with very fine emery cloth to return the surface as nearly as possible to the untreated condition before the soot coating was applied. During the evaluation of the sample surfaces for secondary electron emission characteristics, tests were routinely performed at two or more locations on each half of the disk surface. This procedure helped to ensure the validity of the data since the well-known and readily repeatable very low secondary electron characteristics of soot provided a standard that would immediately indicate errors in procedure or instrument function should they occur.

The surfaces studied in this investigation were evaluated for true secondary electron emission and reflected primary electron characteristics at 11 primary electron beam energy levels from 200 to 2000 eV for each of 6 beam impingement angles from 0° (directly impinging) to 60° (oblique). For each angle the electron gun was focused to produce a spot diameter at the sample of about 10 μm. Tests were routinely repeated with identical conditions, and yielded repeatable results (within limits of measurement) in every instance. Scanning electron microscope examinations made after lengthy periods of testing revealed no observable surface damage from electron beam impingement for any of the surfaces.

True secondary electron emission.—In true secondary electron emission, electrons undergo inelastic collisions at or near the solid surface that is undergoing electron bombardment, and the electrons are emitted from that surface with

energies of the order of a few tens of electron volts. A sample-biasing method that is described in detail in reference 8 was employed to determine the true secondary electron emission characteristics of the surfaces investigated in this study. Briefly, with the electron beam focused on the sample surface at a given beam energy level, the measured sample-to-ground current was taken to be the total beam current minus the secondarily emitted current. When an appropriate positive bias voltage (in this case, 90 V) was then applied to the sample, the true secondary electrons were retained by the sample, and the resulting measured sample-to-ground current was taken to be the total beam current. The true secondary electron emission ratio δ, or ratio of true secondarily emitted electrons to primary electrons, was calculated by the expression

$$\delta = \frac{I_b - (I_b - I_s)}{I_b}$$

where

$I_b - I_s$ beam current minus secondarily emitted current (0.048 to 3.32 μA in this study)

I_b beam current (0.132 to 4.91 μA in this study)

Reflected primary electron yield.—Reflected primary electrons are electrons that experience elastic collisions at a solid surface undergoing electron bombardment and are reflected from the surface with energies equal to or very nearly equal to the primary electron beam energy. The method for evaluating the reflected primary electron yield for the surfaces studied in this investigation is a modification of that used in reference 3. The Auger CMA was used to characterize the relative reflected primary yield at each primary electron beam energy level investigated. The quantity used as a measure of the relative values of reflected primary yields from different surfaces at a given primary electron beam energy and impingement angle was the "reflected primary electron yield index." This is the ratio of the amplitude of the elastic energy peak for a given surface and a given primary electron energy to the amplitude of the elastic energy peak for the control soot surface at the same beam impingement angle and primary electron beam energy. The reflected primary electron yield index ρ is given by

$$\rho = \frac{D_{sample}}{D_{control}}$$

where

D_{sample} elastic curve amplitude for sample surface at a given primary electron beam energy and impingement angle

$D_{control}$ elastic curve amplitude for soot control surface at the same given primary electron beam energy and impingement angle

As has been stated, soot was selected for the control surface, as it was in reference 3, because of its known extremely low

secondary electron emission characteristics and its ability to be readily reproduced.

Note that the index ρ used in this study is different from another index π used by the authors in earlier publications, where $D_{control}$ was defined as the elastic curve amplitude for the soot control surface at 1000-eV primary electron beam energy. The index ρ used here is considered to be a more appropriate descriptor since it realistically indicates an increase in reflected primary electron yield from a surface with increasing primary electron beam energy. Furthermore, it provides for a very useful comparison of measured reflected primary electron yield levels for surfaces over a range of primary electron energies for specific beam impingement angles. Because of possible differences between CMA electron acceptance as a function of beam angle, it is considered better practice to compare characteristics for several surfaces at a single angle rather than for a single surface at several angles.

Note that the reflected primary electron yield that was measured in this study was based only on those electrons that were accepted into the annular analyzer port of the Auger CMA. This is the most important direction of reflected primary yield from the standpoint of MDC efficiency since the reflected primary electrons can retrace the paths of the primary electrons and re-enter the interaction region of the TWT. Although this method does not determine the absolute value of the reflected primary electron yield, it serves the important purpose of permitting comparison of this property for different surfaces.

Experimental Results

Surfaces Investigated

Scanning electron microscope photomicrographs of the sample surfaces studied in this investigation are presented in figure 3. An untreated, or simply machined, OFHC copper surface is shown in figure 3(a). This surface is typical of the
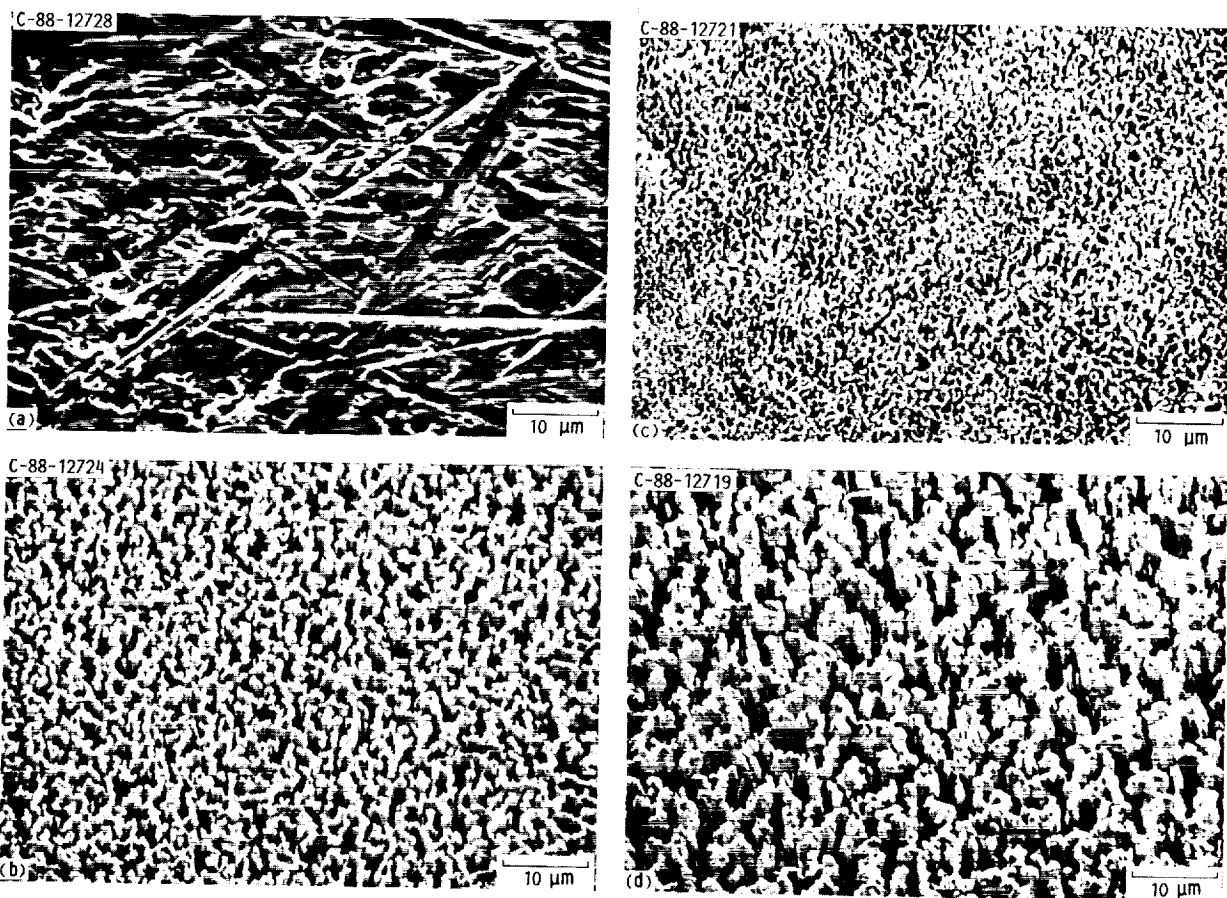
(a) Untreated OFHC copper surface.
(b) Sample 1; textured OFHC copper surface; surface current density, 5mA/cm^2; texturing period, 2 hr; temperature, 447 °C.
(c) Sample 2; textured OFHC copper surface; surface current density, 6 mA/cm^2; texturing period, 1 hr; temperature, 537 °C.
(d) Sample 3; textured OFHC copper surface; surface current density, 6 mA/cm^2; texturing period, 1.5 hr; temperature, 533 °C.

Figure 3.—Scanning electron microscope photomicrographs of untreated OFHC copper surfaces and of molybdenum-masked, ion-textured OFHC copper surfaces. Angle with surface, 30°. Common texturing parameters: accelerating potential, 1500 V dc; argon flow rate, 70 to 75 std cm^3/min; vacuum chamber pressure, 3.99×10^{-3} to 5.32×10^{-3} Pa (3×10^{-5} to 4×10^{-5} torr). (Temperatures noted are for sample receptacle at end of texturing period.)

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other sample substrates included in the study before they were ion textured. The randomly directed scratches seen on the untreated surface were probably caused by postmachining handling; the samples were only gently abraded during the cleaning process described earlier to remove dust or oil film which had accumulated during fabrication. Figure 3(b) to (d) displays the surface features of the three molybdenum-masked OFHC copper samples included in this study. The surface shown in figure 3(b) is designated as Sample 1. It was processed in the manner described in an earlier section of this paper for a period of 2 hr with a measured surface current density of 5 mA/cm^2 and a maximum (end of run) temperature of 447 °C (as measured by a support-structure-mounted thermocouple in contact with the sample). This surface, characterized by a dense array of straight-walled, blunt projections, appears to be very uniform with average feature height and separation being about 5 and 3 μm, respectively. Secondary electron emission characteristics measurements made with this sample indicate, as will be described fully in a later section of this paper, a surface which could have a significant potential for the MDC electrode application because it has emission characteristics that are sharply lower than those of untreated OFHC copper.

In an effort to develop a textured surface equivalent to that of Sample 1, but with a shorter, and therefore less costly, texturing period, Samples 2 and 3 were produced. (Surface photomicrographs of Samples 2 and 3 are presented in figure 3, parts (c) and (d), respectively.) The surface current density was increased to 6 mA/cm^2 and the texturing period was reduced to 1 hr for the processing of Sample 2 (fig. 3(c)), during which time the measured peak temperature reached 537 °C. The projection formation of Sample 2 is much less mature than that of Sample 1, with apparent average height and separation of about 1.5 and 1 μm, respectively. The less mature feature development of this sample permits the surface irregularities of the untreated substrate (typified in fig. 3(a))

to be easily recognized. Another experiment was then performed in a further effort to produce a textured surface whose appearance more nearly approximates that of Sample 1, but with a texturing period shorter than 2 hr. The surface current density was maintained at 6 mA/cm^2, as with Sample 2, but the texturing period was increased to 1.5 hr with a resulting measured peak temperature of 533 °C. These conditions produced Sample 3, the surface features of which are shown in figure 3(d). The apparent average projection height and spacing for this sample are about 7 and 5 μm, respectively. The surface features of Sample 3 are obviously much larger than those of Samples 1 and 2, indicating a strong interdependency of surface feature maturity (size, height, and spacing), sample current density, and texturing period for molybdenum-masked, ion-textured OFHC copper.

The molybdenum-masked, ion-textured OFHC copper surface differs markedly from untreated OFHC copper by unaided visual observation as well as by microscopic examination, as demonstrated in figure 4. The textured surface appears to be much darker than the untreated surface because of the light-absorbing effect of the textured sample's complex surface morphology.

Despite the rather fragile appearance of the ion-textured OFHC copper surfaces shown in figure 3, they are quite resistant to damage by most of the handling procedures normally encountered in MDC and TWT fabrication, such as fixturing, removal of dust particles by low pressure inert gas purging, or light finger contact. Tool contact with the textured surfaces and ultrasonic cleaning, however, are to be avoided.

Sample Surface Auger Spectroscopic Examinations

The surface of each sample included in this study was subjected to Auger spectroscopic examination both before and after the sample was baked out or degassed at 500 °C for several hours. The Auger spectrum for the ion-textured OFHC
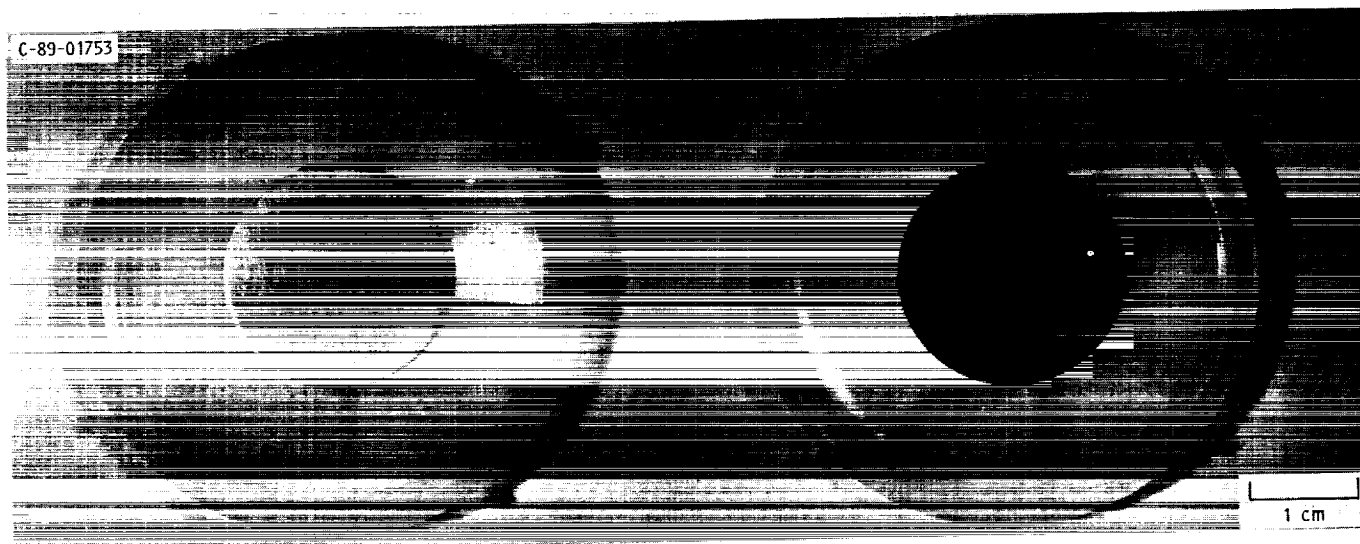

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1 cm

Figure 4.—Contrast in appearance of untreated (left) and molybdenum-masked, ion-textured OFHC copper surfaces. (Samples are shown in storage containers.)
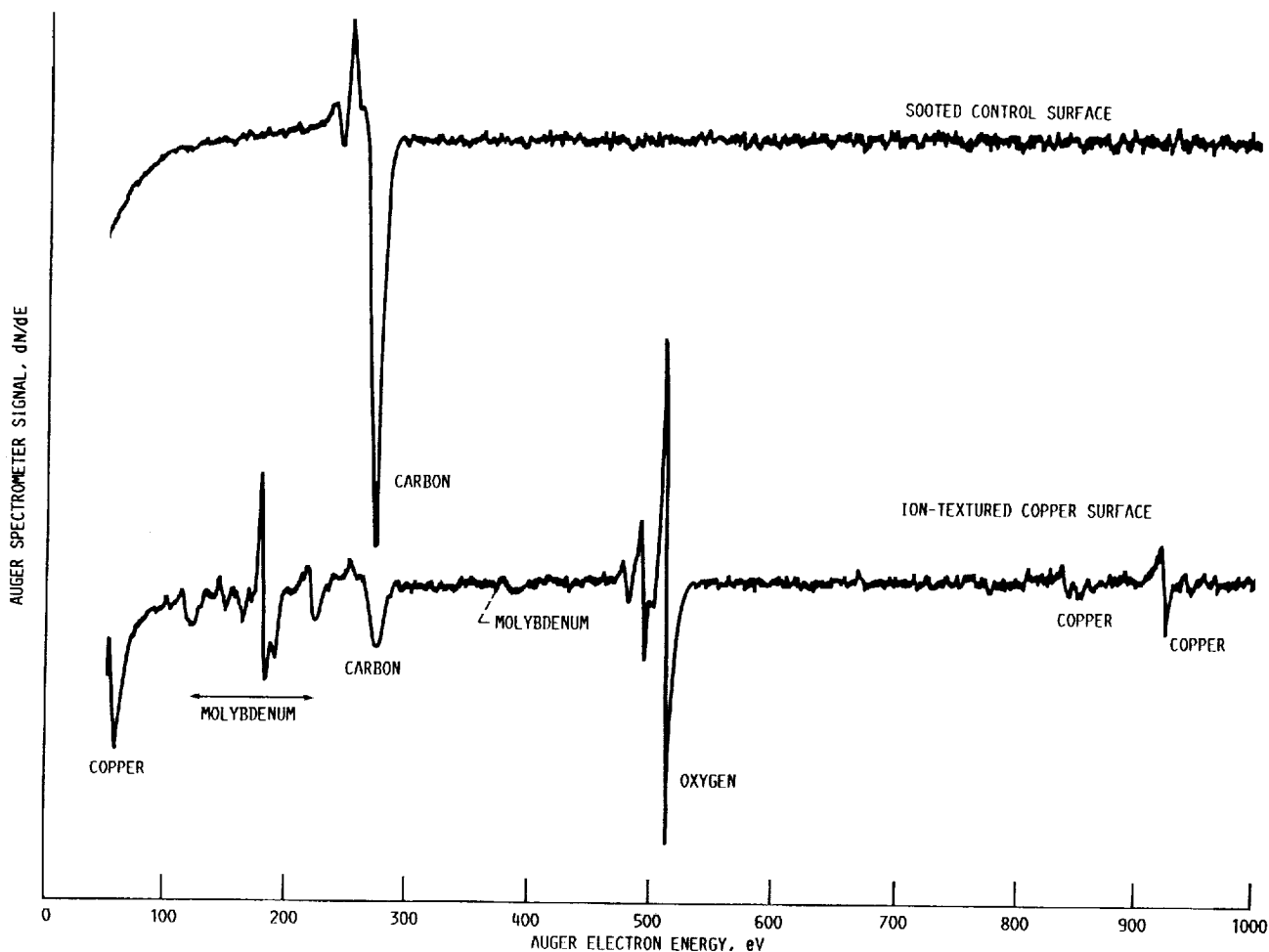
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Figure 5.—Auger spectra for control and molybdenum-masked, ion-textured OFHC copper surfaces.

copper surface of Sample 1 before bakeout is presented in figure 5, along with that for the soot-coated control surface portion of the sample. For comparison, the instrument sensitivity settings were identical for both traces. Since corresponding spectra for all three textured samples, both before and after bakeout were quite similar, only those traces shown in figure 5 are presented. Only small decreases in the amplitude of the oxygen peak were noted between prebakeout and postbakeout Auger spectra for the ion-textured OFHC copper surfaces. The presence of molybdenum, the "seeding" material, is indicated by a prominent peak pattern on the curve for ion-textured OFHC copper. It is this covering film of molybdenum, along with the emission-attenuating, highly textured surface, that contributes to the amplitude of the copper Auger peak being significantly smaller than that which would be expected for a clean copper surface. The carbon and oxygen indicated as being present are tenacious surface contaminants which resist removal by the bakeout methods used in this study. Argon, the ion source gas, is not evident on the textured sample Auger trace. As would be expected, carbon is the only element indicated on the Auger spectrum for the sooted control surface.

Secondary Electron Emission Measurements

The experimental results presented in this study are specific values for an individual test series performed for each sample surface, as distinguished from averaged or mean values for several near-identical test conditions. Based on experience gained in conducting a large number of similar test series with OFHC copper and other materials, the results presented are considered to be typical for the respective sample surfaces. The samples were carefully examined by scanning electron microscopy before being placed in the test facility to ensure that the surface areas chosen for examination were typical.

Neither the ion-texturing procedures described in this study or the test results achieved are represented here as being optimum from the standpoint of secondary electron emission suppression. The study does, however, demonstrate that OFHC copper may be ion textured in the manner described to effectively reduce its secondary electron emission properties relative to those of untreated OFHC copper. It can be reasonably expected that further experimentation and development would result in even greater reductions in the emission characteristics of ion-textured OFHC copper.

True secondary electron emission ratio.—The true secondary electron emission ratio δ generally increased with increasing electron beam impingement angle from direct (0°) to oblique (60°) over the entire primary electron energy range (200 to 2000 eV) for all of the sample surfaces included in this study. This trend is shown in figure 6(a) to (d) for untreated OFHC copper (data taken from ref. 4) and for the molybdenum-masked, ion-textured OFHC copper Samples 1, 2, and 3, respectively. Experimental data presented in references 4, 8, 10, and 11 display the same general trends for ion-textured graphite; textured carbon on OFHC copper; tantalum-masked, ion-textured OFHC copper; and tantalum-masked, ion-textured titanium.

The tendency for the true secondary electron emission ratio for untreated OFHC copper to increase with increasing beam impingement angle, as shown in figure 6(a), is attributed to the impinging electrons penetrating the material to ever-decreasing distances normal to the material surface as the beam impingement angle is increased. The electrons undergoing inelastic collisions have shorter distances to travel to reach and escape the surface, and do so in increasing numbers as the beam angle is increased.

The surface of the ion-textured OFHC copper samples is characterized by a dense array of rather blunt, straight-sided projections that are normal to the underlying OFHC copper substrate, as shown in figure 3. The appearance of the surface is quite similar to that of the tantalum-masked, ion-textured OFHC copper surface examined in reference 4 (see fig. 3(b) of that publication). For this surface, many of the electrons strike the projection walls or base locations when the beam impinges directly (0°) or nearly directly. Many of the true secondary electrons generated in these locations then are intercepted by the nearby peak walls, reducing the net emission from the projected surface area. As the electron beam impingement angle is increased, beam penetration into the complex surface structure is reduced. The resulting reduced secondary electron trapping effect permits the net secondary electron emission to increase.

Examination of figure 6(a) to (d) indicates that the measured true secondary electron emission ratio of any of the ion-textured OFHC copper samples is only about 40 percent of that of the untreated OFHC copper over the entire ranges of primary electron energy and beam impingement angles included in the study. In spite of the significant differences in the appearances of the surface features of the three ion-textured OFHC copper samples (fig. 3), the true secondary electron emission ratio values over the range of variables included in the study are remarkably similar for Samples 1, 2, and 3. For this combination of masking and substrate materials and general ion-texturing process, the reduction in true secondary electron emission ratio relative to that of the untreated surface is apparently not a strong function of developed surface features. This tendency is in contrast to the observed characteristics of the ion-textured carbon surface sputter-applied to the OFHC copper surface described in

reference 10. In that study, a significant direct relationship between true secondary electron emission ratio and surface development toward "maturity," or ultimate feature growth, was observed.

Reflected primary electron yield index.—Curves presenting the reflected primary electron yield index ρ as a function of primary electron beam energy appear in figure 7(a) to (f). The index characteristics for each of the three molybdenum-masked, ion-textured OFHC copper samples studied, as well as for the untreated OFHC copper sample (data taken from ref. 4), are presented separately for each of the six primary electron beam impingement angles investigated.

In contrast to the very similar true secondary electron emission ratio characteristics observed for the three ion-textured OFHC copper samples (each of which were processed to a different degree of surface development), the reflected primary yield index traits are significantly different. An examination of figure 7(a) to (f) shows that Sample 1 (processed for 2 hr with a surface current density of 5 mA/cm^2) displays lower yield index levels over the entire range of variables studied than Sample 3 does (processed for 1.5 hr at 6 mA/cm^2). Continuing the comparison, Sample 3 displays lower yield index characteristics than Sample 2 does, (processed for 1 hr at 6 mA/cm^2).

In an earlier study (ref. 4) it was observed that, with the method of measurement used in this investigation, untreated OFHC copper exhibits generally decreasing levels of reflected primary electron yield index with increasing beam impingement angle over the primary electron beam energy range investigated. For this surface, impinging electrons that undergo elastic collisions reflect in directions away from the Auger CMA increasingly as the beam impingement angle is increased. This results in increasingly smaller measurements of reflected primary electron yield. It was also observed that tantalum-masked, ion-textured OFHC copper (ref. 4), ion-textured graphite (refs. 4 and 8), and ion-textured carbon (ref. 10) all display increasing reflected primary electron yield index measurements with increasing beam impingement angle over the same electron beam energy range. This beam impingement angle influence is attributed to the progressively increasing surface feature wall surface area presented normal to the Auger CMA as the angle is increased, in turn resulting in increasing reflected primary electron detection.

The net result of these opposing trends is a reduction of the differences between the reflected primary electron yield indices of the untreated OFHC copper and ion-textured OFHC copper samples as the beam impingement angle is increased. In spite of this tendency, however, the ion-textured samples all exhibited sharply lower reflected primary electron yield index levels than those of untreated OFHC copper for the conditions of this study. Sample 1, for example, displayed reductions in the index relative to untreated OFHC copper from approximately 85 percent at direct beam impingement (0°) to 67 percent at a 60° beam impingement angle. Samples 2 and 3, similarly, exhibited index reductions at 0° of about 70 and

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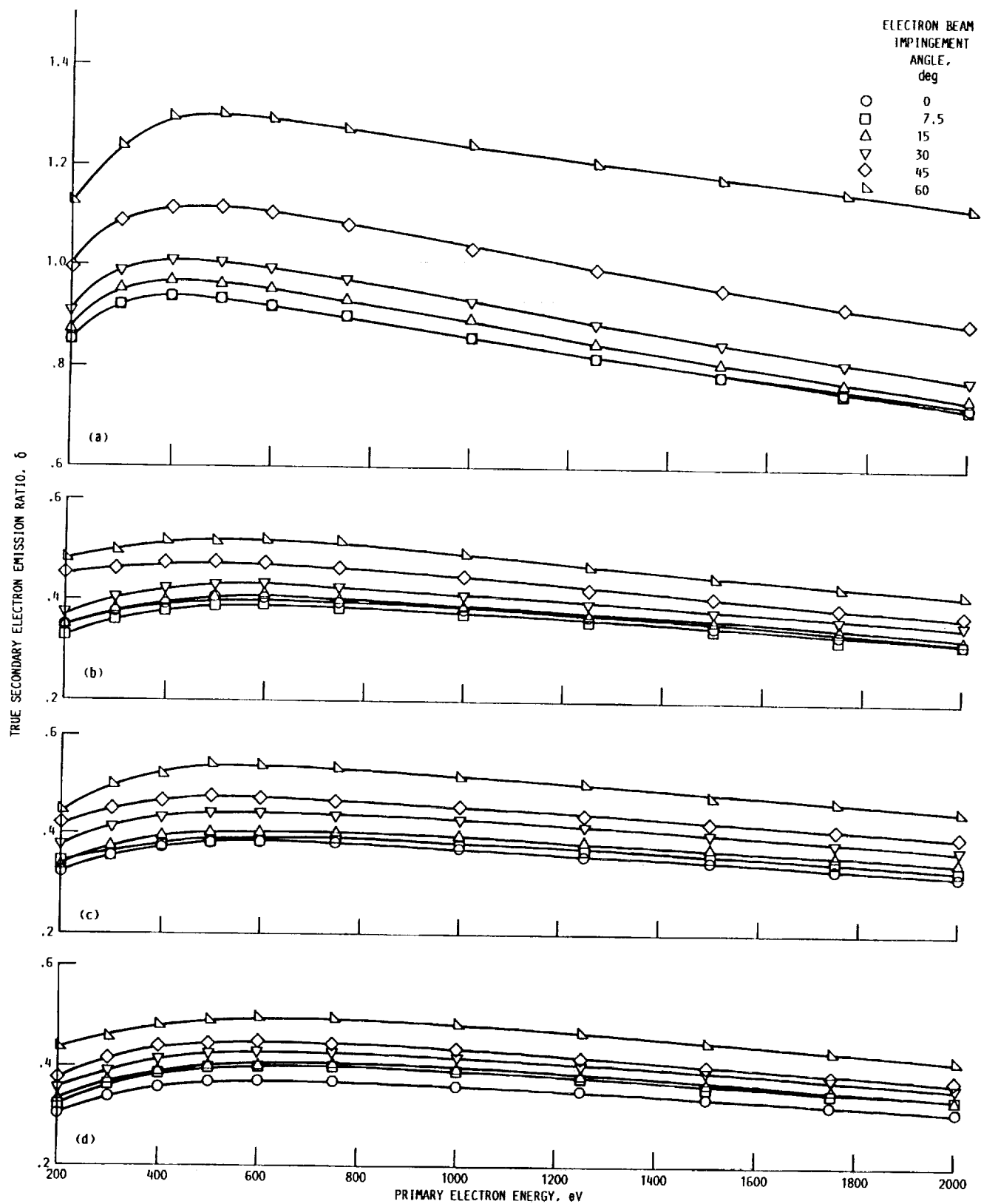
(a) Untreated OFHC copper.
(b) Molybdenum-masked, ion-textured OFHC copper; Sample 1.
(c) Molybdenum-masked, ion-textured OFHC copper; Sample 2.
(d) Molybdenum-masked, ion-textured OFHC copper; Sample 3.

Figure 6.—True secondary electron emission ratio as function of primary electron energy.

(a) Electron beam impingement angle, 0°.
(b) Electron beam impingement angle, 7.5°.
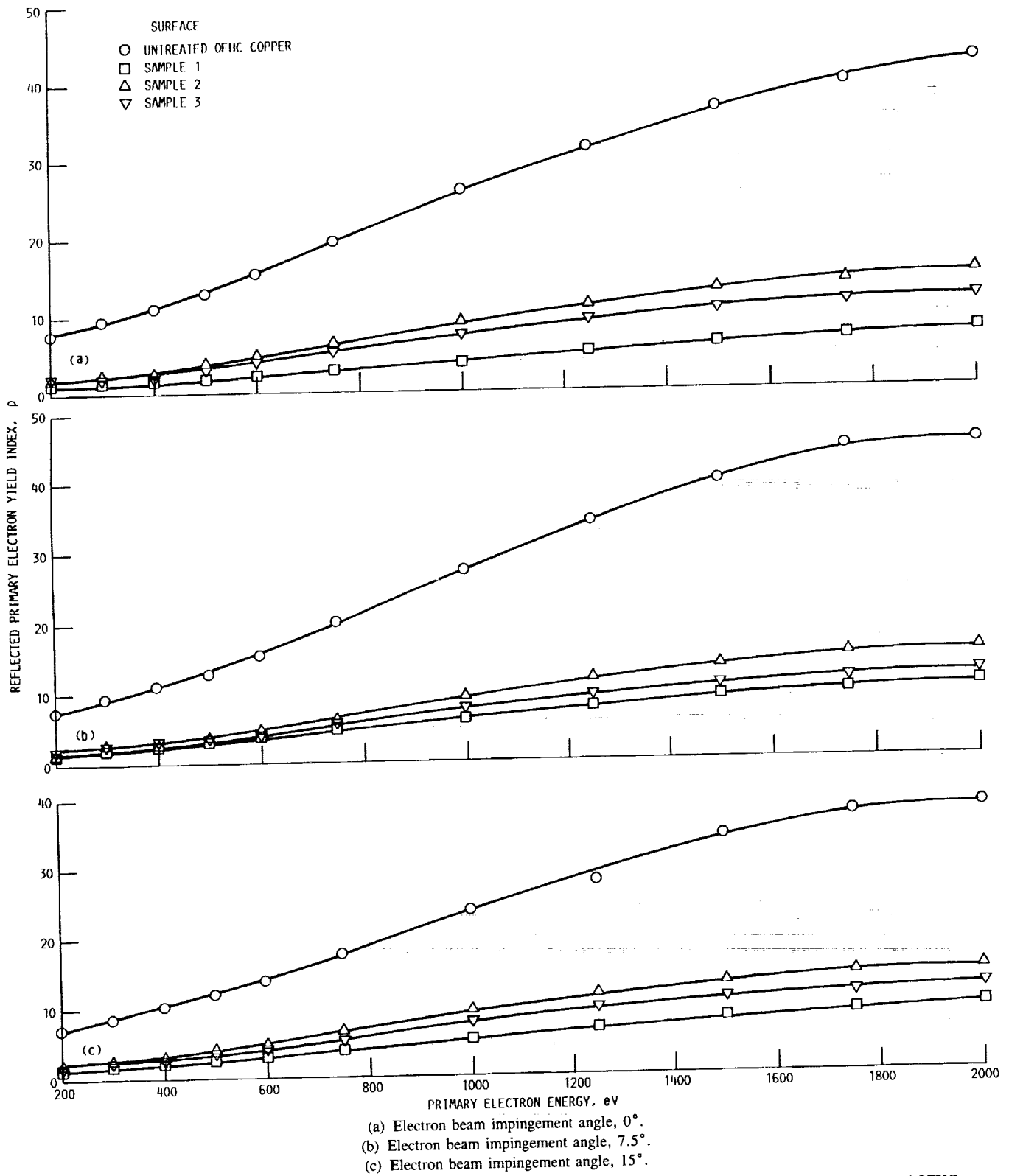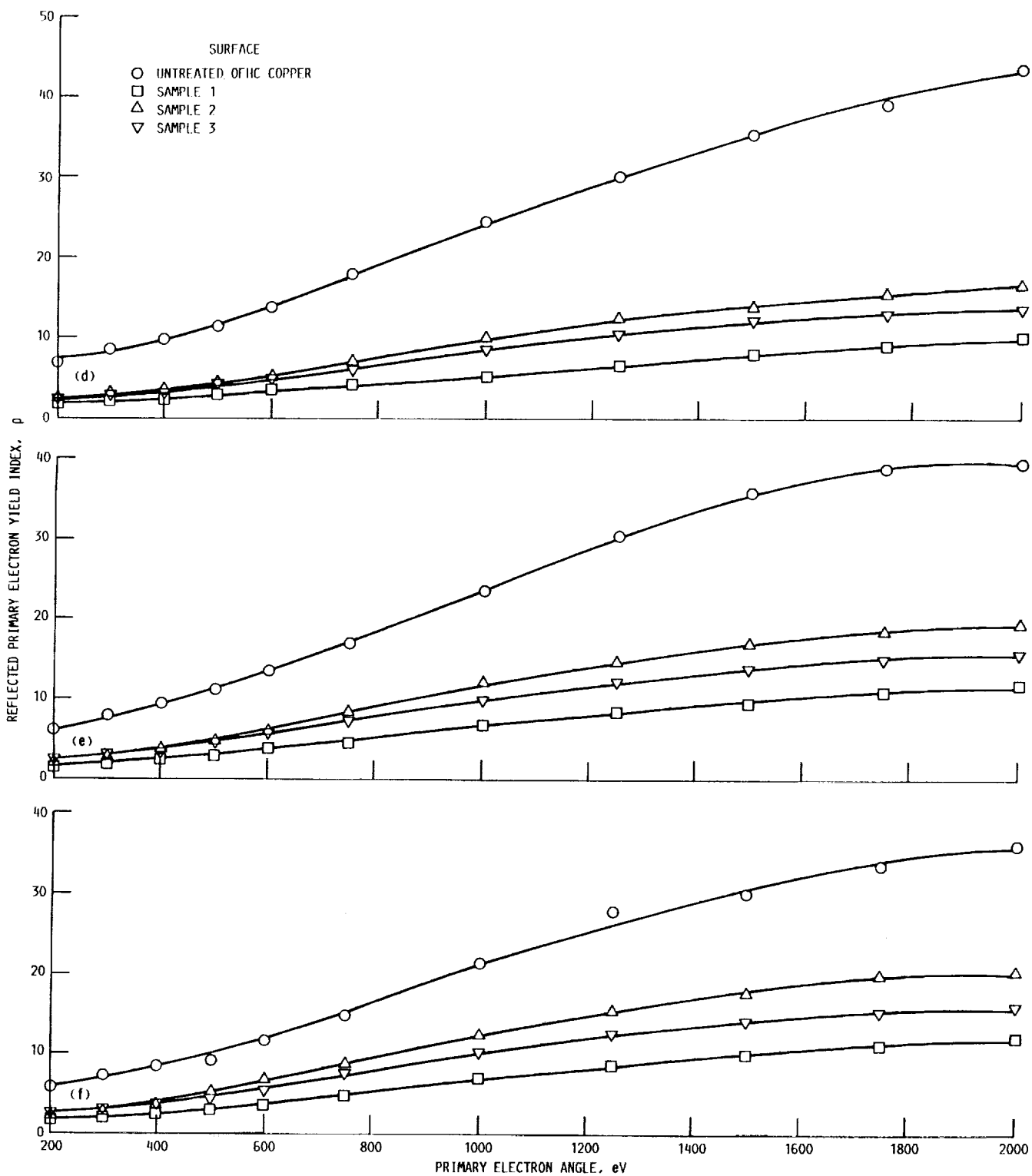(c) Electron beam impingement angle, 15°.

Figure 7.—Reflected primary electron yield index as function of primary electron energy. Samples 1, 2, and 3 are molybdenum-masked, ion-textured OFHC copper.

(d) Electron beam impingement angle, 30°.
(e) Electron beam impingement angle, 45°.
(f) Electron beam impingement angle, 60°.

Figure 7.—Concluded.

73 percent, respectively, and 45 and 48 percent, respectively, at a 60° beam impingement angle.

Although attempting to relate the reflected primary electron yield characteristics of the ion-textured OFHC copper to their physical appearances (fig. 3) is certainly an inexact approach, some observed trends are rather obvious and may be put to use. It has been demonstrated, for example, that Sample 1 (fig. 3(b)) with its well-formed, uniformly sized, and evenly spaced spire formation, suppresses the reflected primary electron yield index relative to untreated OFHC copper over the range of variables studied more than does Sample 3 (fig. 3(d)) with its relatively overdeveloped and nonuniform features, and much more than Sample 2 (fig. 3(c)), with its very thin, immature feature development.

Additional experimental studies are certainly required if molybdenum-masked, ion-textured OFHC copper is to be developed for effective secondary electron emission suppression applications, but some guidelines are now apparent. These would include the need for feature uniformity, spire height adequate to conceal substrate surface scratches and machining marks, but less feature development than that of Sample 3, which appears to lead to significant spire grouping or coalescing resulting in a less desirable effective feature aspect ratio for primary electron yield suppression.

Conclusions

The secondary electron emission characteristics of three molybdenum-masked, ion-textured OFHC copper samples— each processed in a different way—were experimentally determined and compared with each other and with the emission characteristics of an untreated OFHC copper sample. The processes that were developed to produce the textured surfaces and the testing procedures are described. The purpose of the study was to develop a basically OFHC copper surface having low secondary electron emission characteristics. This surface, even with small amounts of the molybdenum-masking material remaining, is compatible with conventional traveling-wave tube (TWT) fabrication procedures. It therefore is a promising candidate for the electrodes of multistage depressed collectors (MDC's) for microwave TWT's used in space communications and other applications. True secondary electron emission and relative reflected primary electron yield measurements were made for the samples over a range of primary electron beam energies from 200 to 2000 eV and at beam impingement angles from direct (0°) to oblique (60°).

Although no rigorous attempt was made to texture the samples in such a way as to produce the greatest secondary electron emission suppression, all of the textured samples displayed much lower emission characteristics than those of untreated OFHC copper over the range of test parameters examined. At direct electron beam impingement maximum values, the true secondary electron emission and relative reflected primary electron yield were lower than those of untreated OFHC copper by as much as 60 and 85 percent, respectively. These results strongly indicate the potential effective application of the textured OFHC copper for MDC electrodes. Surprisingly, all of the textured samples displayed similar true secondary electron emission characteristics regardless of the texturing procedure used or the maturity of the surface features that resulted. One sample, however, exhibited clearly lower levels of reflected primary electron yield index than the others. Further development of the ion-texturing of OFHC copper by the means described in this study may result in surfaces displaying even lower secondary electron emission characteristics.

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References

1. Kosmahl, H.G.: A Novel, Axisymmetric, Electrostatic Collector for Linear Beam Microwave Tubes. NASA TN D-6093, 1971.

2. Kosmahl, H.G.; and Ramins, P.: Small-Size 81- to 83.5-Percent Efficient 2- and 4-Stage Depressed Collectors for Octave-Bandwidth High-Performance TWT's. IEEE Trans. Electron Devices, vol. ED-24, No. 1, Jan. 1977, pp. 36–44.

3. Forman, R.: Secondary-Electron-Emission Properties of Conducting Surfaces with Application to Multistage Depressed Collectors for Microwave Amplifiers. NASA TP-1097, 1977.

4. Curren, A.N.; and Jensen, K.A.: Secondary Electron Emission Characteristics of Ion-Textured Copper and High-Purity Isotropic Graphite Surfaces. NASA TP-2342, 1984.

5. Kohl, W.H.: Handbook of Materials and Techniques for Vacuum Devices. Reinhold Publishing Corp., 1967.

6. Curren, A.N.: Carbon and Carbon-Coated Electrodes for Multistage Depressed Collectors for Electron Beam Devices—A Technology Review. IEEE Trans. Electron Devices, vol. ED-33, no. 11, Nov. 1986, pp. 1902–1914.

7. Ebihara, B.T.; Ramins, P.; and Peet, S.: Traveling-Wave-Tube Efficiency Improvement by a Low-Cost Technique for Deposition of Carbon on Multistage Depressed Collector. NASA TP-2919, 1987.

8. Curren, A.N.; and Jensen, K.A.: Beam Impingement Angle Effects on Secondary Electron Emission Characteristics of Textured Pyrolytic Graphite. NASA TP-2285, 1984.

9. Wehner, G.K.: Cone Formation as a Result of Whisker Growth on Ion Bombarded Metal Surfaces. J. Vac. Sci. Technol. A, vol. 3, no. 4, Jul./Aug. 1985, pp. 1821–1835.

10. Curren, A.N.; and Jensen, K.A.: Textured Carbon on Copper: A Novel Surface with Extremely Low Secondary Electron Emission Characteristics. NASA TP-2543, 1985.

11. Curren, A.N.; Jensen, K.A.; and Blackford, G.A.: Secondary Electron Emission Characteristics of Untreated and Ion-Textured Titanium. NASA TP-2902, 1989.

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16. Abstract

A method for producing a uniform, highly textured surface on oxygen-free, high-conductivity (OFHC) copper by ion bombardment using sputtered molybdenum as a texture-inducing masking film was developed and used to provide samples for study. The purpose was to develop a basically OFHC copper surface having very low secondary electron emission characteristics. Surfaces having low secondary electron emission are a requirement for the electrodes of very high efficiency multistage depressed collectors (MDC's). Such MDC's are used in microwave amplifier traveling-wave tubes for space communications and other applications. OFHC copper is the material most commonly used for MDC electrodes because it has high thermal conductivity, it is easy to machine, and its fabrication and brazing procedures are well-established. However, its untreated surface displays relatively very high levels of secondary electron emissions. Textured OFHC copper samples were tested for true secondary electron emission and relative reflected primary electron yield at primary electron beam energy levels from 200 to 2000 eV and at direct (0°) to oblique (60°) beam impingement angles. The test results for three of the samples, each of which was processed in a slightly different way, are compared with each other and with test results for a machined OFHC copper sample. Although the textured samples are not represented here as having been processed optimally, their measured secondary electron emission characteristics are significantly lower than those of the untreated OFHC copper sample over the range of conditions studied. Importantly, the relative reflected primary electron yield of one of the textured samples is conspicuously lower than that of the others. Clearly, with further development, the molybdenum-masked ion-textured OFHC copper surface will be a promising material for high-efficiency MDC electrodes.

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