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13. ABSTRACT *(Maximum 200 words)*
This final technical report summarizes the research activities over the last year of this grant. New time-dependent secondary electron yield (S.E.Y) measurements, including both true secondary emission and backscattering, have been made on materials thought to be suitable for low yield vacuum electronic applications such as collectors in High Power Microwave (HPM) tubes and beam-facing components in particle accelerators. Measurements of the angular dependence of S.E.Y. have also been performed and compared well with the literature. Boron-carbide-sprayed copper substrates, provided by Calbazas Creek Research, Inc., have also been initially characterized, and will be presented in a paper at IVEC 2005. The dependence of true secondaries on incident beam energy has been measured, but its interpretation has yet to be completed. These open questions will be resolved under the auspices of a follow-on grant.

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"Measurements of Secondary Electron Yield from Materials with Application to Depressed Collectors"

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TABLE OF CONTENTS

TABLE OF CONTENTS **3**
LIST OF FIGURES **4**
I. INTRODUCTION **5**
II. STATUS OF THE PROJECT **6**
A. Experimental Description – Low-Energy Measurements 6
B. Targets used and SEM images 9
C. Preliminary low-energy measurement results 10
D. Preliminary Heat distribution results in copper using ANSYS 12
Conclusions 15
III. REFERENCES **17**
IV. PERSONNEL, PUBLICATIONS, INTERACTIONS, AWARDS **18**
PERSONNEL 18
PUBLICATIONS 18
RECOGNITION 20
NEW DISCOVERIES, INVENTIONS, PATENTS 20

LIST OF FIGURES

FIGURE 1. BEAM CURRENT OF ELG-2 ELECTRON GUN VS. BEAM ENERGY FOR TWO VALUES OF CATHODE CURRENT. 6
FIGURE 2. CUT-AWAY VIEW OF THE UHV CHAMBER. 1 – ELG-2 ELECTRON GUN; 2 – SAMPLE HOLDER; 3 – FARADAY CUP; 4 – THERMOCOUPLE. 7
FIGURE 3. RGA SCAN SNAPSHOTS AT 5.9×10^{-8} TORR AND 6.25 EV (SMALLER PICKS) AND 1000 EV BEAM ENERGIES. 7
FIGURE 4. SAMPLE HOLDER. 1 – MACHINABLE CERAMIC; 2 – COPPER WIRE CONNECTING TARGET TO CONFLAT FLANGE WITH BNC FEEDTHROUGHS. 8
FIGURE 5. SAMPLE HOLDER AFTER MODIFICATION. 8
FIGURE 6. SEM IMAGES OF COPPER SAMPLE. 9
FIGURE 7. SEM IMAGES OF COPPER SAMPLE PLASMAS-SPRAYED WITH BORON CARBIDE. 10
FIGURE 8. TARGET CURRENT VS. BEAM ENERGY FOR CLOCKWISE AND COUNTERCLOCKWISE ROTATION OF COPPER TARGET. 10
FIGURE 9. TARGET CURRENT OF COPPER VS. BEAM ENERGY AND ANGLE OF INCIDENCE FOR CLOCKWISE AND COUNTER CLOCKWISE ROTATION OF TARGET. 11
FIGURE 10. S.E.Y. Δ OF COPPER VS. BEAM ENERGY FOR NORMAL AND OBLIQUE INCIDENCE OF PRIMARY ELECTRONS. 12
FIGURE 11: CONTOUR PLOT OF TRANSIENT THERMAL CONDUCTION IN A COPPER DISC. 13
FIGURE 12: GRAPH OF THE TRANSIENT THERMAL RESPONSE OF A COPPER DISC. 13
FIGURE 13. VARIOUS STAGES (INCREASING TIME) IN A 10 SECOND THERMAL SIMULATION OF A SAMPLE WITH 100 K (LEFT) AND 500 K (RIGHT) TEMPERATURES IMPOSED AT ENDS AND TOP SURFACE BEING RADIATED TO BY A NODE AT 1000 K. 13
FIGURE 14. VARIOUS STAGES (INCREASING TIME) IN A 10 SECOND THERMAL SIMULATION OF A SAMPLE WITH (LEFT) 100 K AND (RIGHT) 500 K TEMPERATURES IMPOSED AT ENDS AND TOP SURFACE BEING RADIATED TO BY A NODE AT 1000 K. 14
FIGURE 15. VARIATION OF RADIATION WITH TIME (IN SECONDS). 14
FIGURE 16. GRADIENTS ON TOP SURFACE PRODUCED DUE TO RADIATION BY A NODE AT 25000 K. 15

I. INTRODUCTION

In modern vacuum electronic systems, the interaction of energetic particles with solid surfaces is playing an increasing role in determining the operating characteristics of the device, as electron beam energy, current, and pulse duration continue to increase. The production of secondary electrons on surfaces exposed to electron beams and oscillating electromagnetic fields can have deleterious effects on the operation of these devices, such as reduced efficiency in High Power Microwave (HPM) tubes and degraded performance of particle accelerators. Characterizing the secondary electron yield (S.E.Y.) of materials used for these applications is an important part of improving the general understanding of electron-material interactions, and may allow for significant gains in device performance if low secondary yield can be identified. This is particularly true in the context of depressed collectors in high average power gyrotrons.

The published secondary electron yield reported for a given material varies often by ±7% from one laboratory to another. The discrepancy in these data may be due to various factors including the following: surface morphology, surface contamination (*i.e.* oxidation layers and adsorbed gases), measurement techniques, cleaning processes, and use of different primary electron beam currents.

This final technical report summarizes our activity-to-date in measuring the S.E.Y. of materials with applications to depressed collectors.

II. STATUS OF THE PROJECT

A. Experimental Description – Low-Energy Measurements

Secondary electrons are usually referred to as "true" if they possess energies less than 50 eV [1]. Thus, to perform S.E.Y. measurements involving so-called "true" secondary electrons, guns capable of producing low-energy electron beams are necessary. By replacing the commercial Kimball Physics electron gun and power supply (model #EGH-6002/EGPS 6002) with an ELG-2 electron gun (energy range 5 eV – 2000 eV) by the same manufacturer, we have performed several DC measurements of S.E.Y. over a low energy range. (Previous measurements were made strictly at high energies.) The ELG-2 gun uses a standard tantalum disk cathode and can deliver 1 μA into an approximately 1 mm spot at a 20 mm working distance and 10 eV. Figure 1 depicts the gun beam current as a function of beam energy for two values of the source (cathode) current.

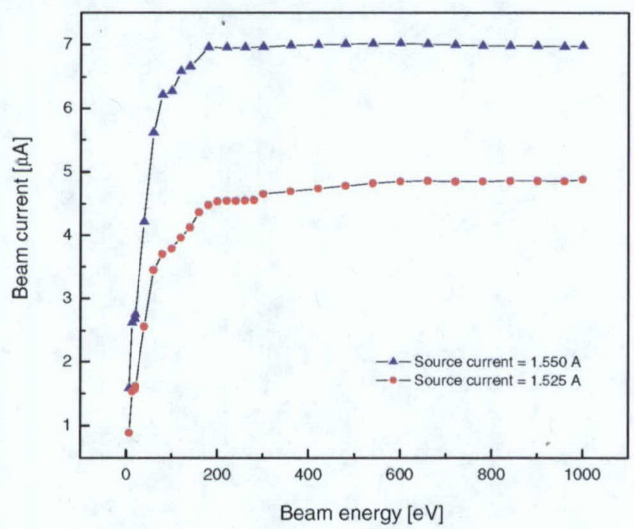

Figure 1. Beam current of ELG-2 electron gun vs. beam energy for two values of cathode current.

Initially, the beam current increases as beam energy is increased and the gun operates in a temperature-limited regime. As the beam energy is further increased, the beam current levels off and the gun enters a space-charge-limited mode of operation.

The gun operation and data acquisition (beam and target currents) are accomplished through the same DAQ/GPIB boards, electrometer (Keithley Instruments, Inc.) and a personal computer running LaBVIEW 6.1 (National Instruments, Inc.) used in the higher energy experiments described in our previous two annual reports. Experiments are performed in an UHV vacuum chamber (modified GEC reference cell), the cut-away view of which is shown in Figure 2. To monitor gas composition in the chamber during pump-down and while taking measurements, a residual gas analyzer (RGA) (MKS instruments, Inc.) is employed. Figure 3 shows a scan snapshot obtained from the RGA at a pressure of 5.9×10^{-8} Torr and 6.25 eV and 1000 eV beam energies.

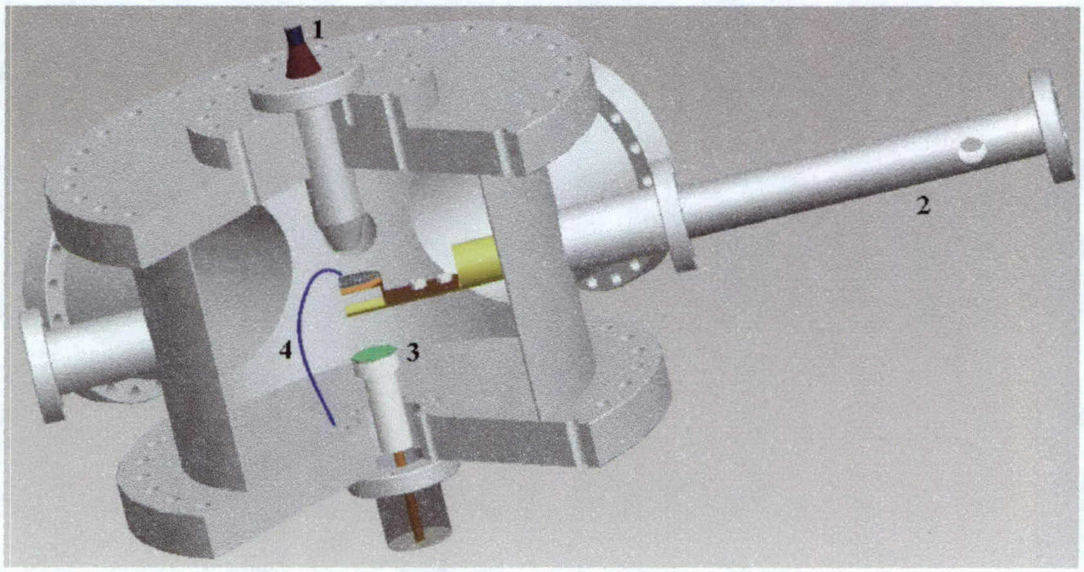

Figure 2. Cut-away view of the UHV chamber. 1 – ELG-2 electron gun; 2 – sample holder; 3 – Faraday cup; 4 – thermocouple.

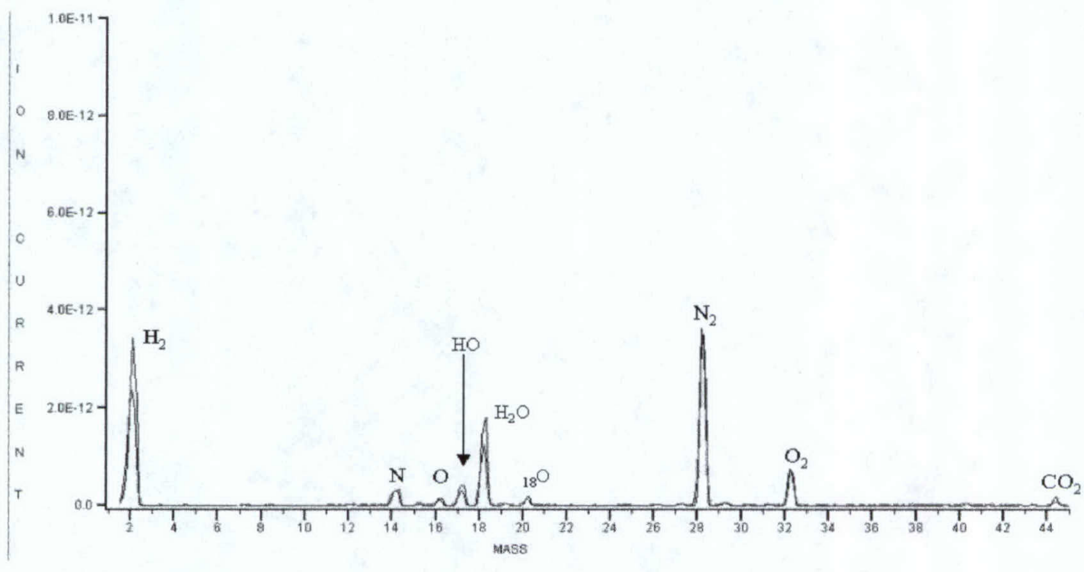

Figure 3. RGA scan snapshots at 5.9×10^{-8} Torr and 6.25 eV (smaller picks) and 1000 eV beam energies.

Low-energy (5 eV – 1000 eV) DC measurements of S.E.Y. were made using a copper target for both normal and oblique incidence of the primary electron beam. DC measurements of the S.E.Y. of a copper substrate plasma-sprayed with boron carbide [2] are under way. The data will be recorded over the full range of the gun: 5 eV to 2 keV. The DC measurements will be followed by measurements in the pulsed regime for comparison. The sample holder used in high-energy measurements, shown in Figure 4, has been redesigned to make it sturdier and less susceptible to field distortion inside the chamber due to dielectric charging, as indicated in Figure 5.

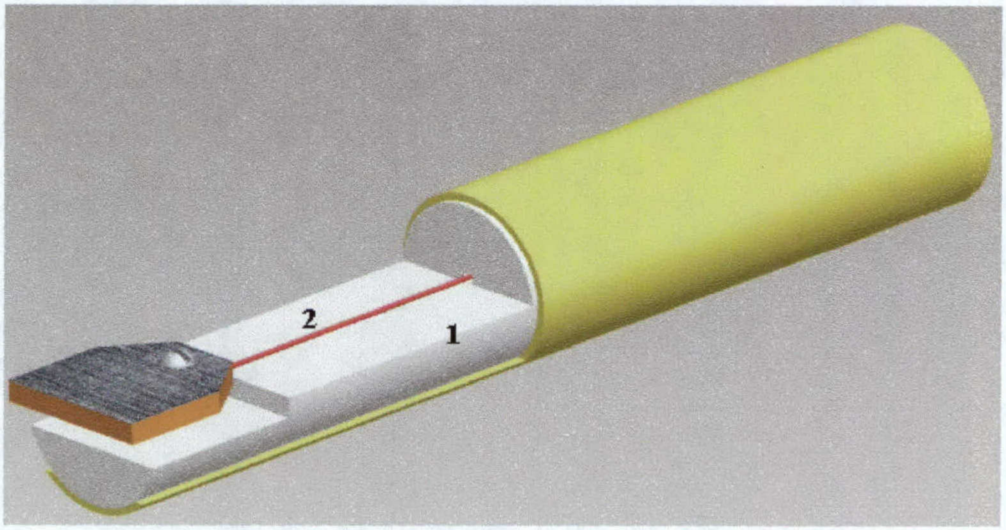

Figure 4. Sample holder. 1 – machinable ceramic; 2 – copper wire connecting target to conflat flange with BNC feedthroughs.

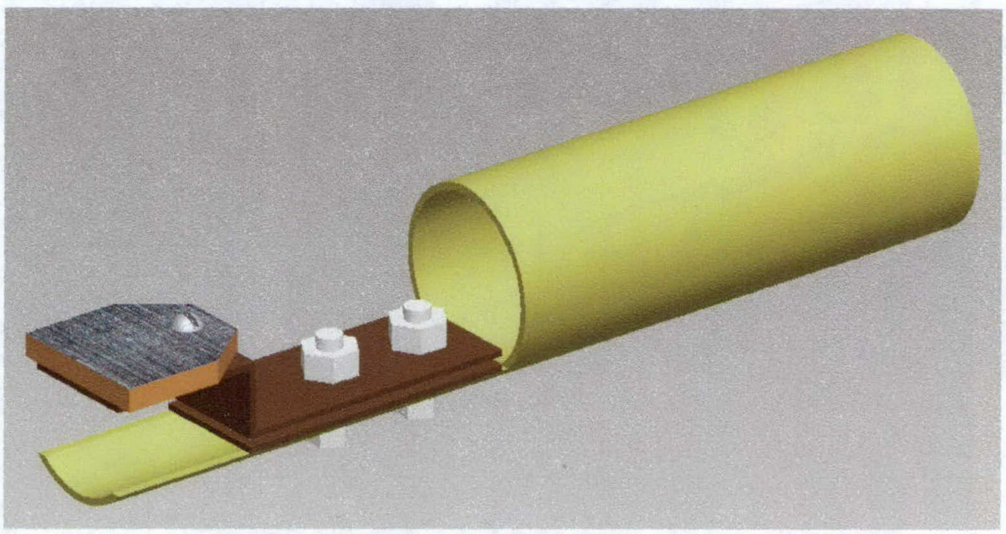

Figure 5. Sample holder after modification.

Although all the measurements so far have been DC, the gun may also be operated in the pulsed mode and we are planning experiments to compare the pulsed results with the DC results.

B. Targets used and SEM images

The samples under study were approximately 25 mm in diameter and 3 mm thick. The copper sample was subjected to mechanical sanding to ensure uniform surface structure and then mechanically cleaned with ethyl alcohol prior to placement into vacuum. No surface preparation was necessary for the boron carbide sample, as it was enclosed in an airtight, dust-free package. Figures 6 and 7 present SEM images of copper and boron carbide at different magnification levels.

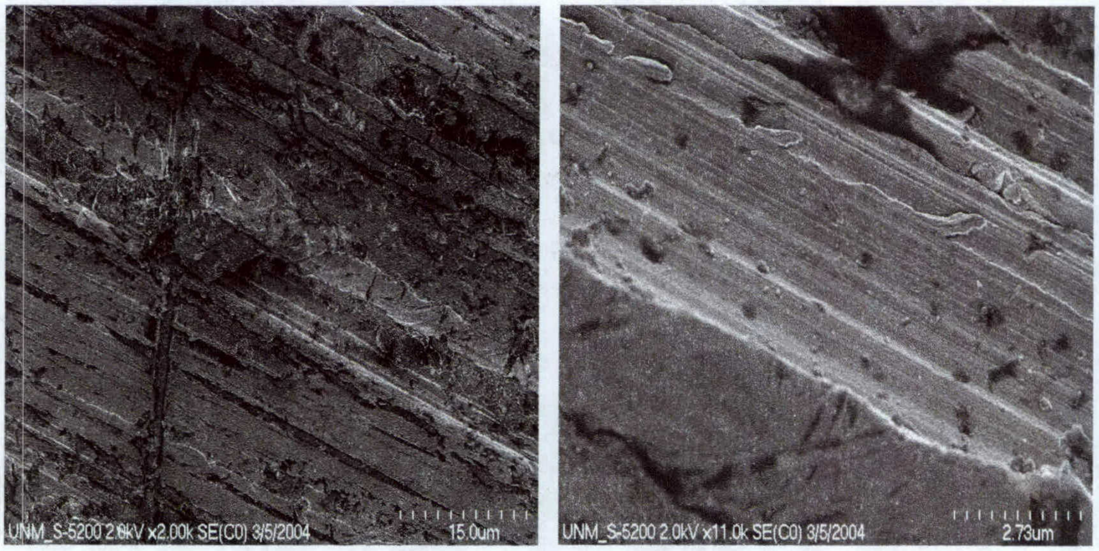

Figure 6. SEM images of copper sample.

It is evident from the SEM pictures that neither of the surfaces is smooth on the micron scale. In addition, the surface of the boron carbide is much rougher than that of copper. Since surfaces with more irregularities tend to exhibit reduced secondary electron emission yields [5], we expect the boron carbide sample to have a lower S.E.Y.

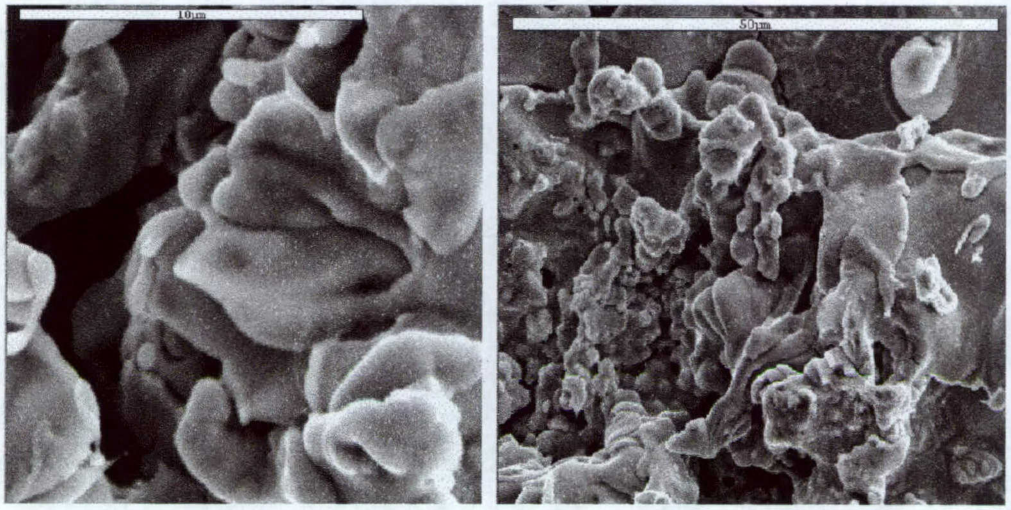

Figure 7. SEM images of copper sample plasmas-sprayed with boron carbide.

C. Preliminary low-energy measurement results

Figure 8 shows a graph of target current vs. beam energy for the copper target at normal and oblique incidence of the primary electron beam. Positive angles indicate clockwise rotation, while negative angles correspond to anticlockwise rotation – angles being measured with respect to the normal incidence of the electron beam.

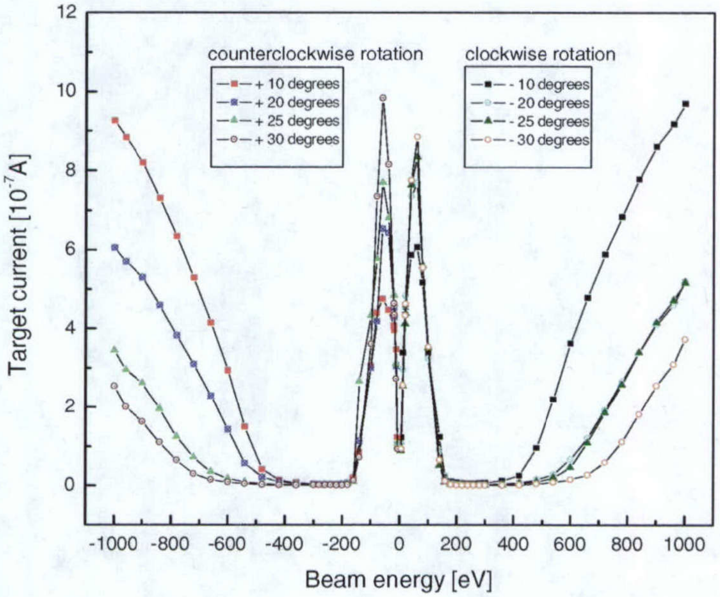

Figure 8. Target current vs. beam energy for clockwise and counterclockwise rotation of copper target.

Rotation of the sample holder is accomplished via a differentially pumped rotary seal. The limitation of rotation, 30° in either direction due to the beam being partially off the sample, was overcome with the new sample holder. We are now are able to achieve a maximum rotation angle of 40°. Evantually, we would like to be able to record data at angles equal to 45° and greater since those angles of incidence are of greatest interest to the study of secondary electron emission in depressed collectors.

Figure 9 displays a 3D plot of target current vs. beam energy and angle of incidence (for clockwise and counter clockwise rotation) for the copper target.

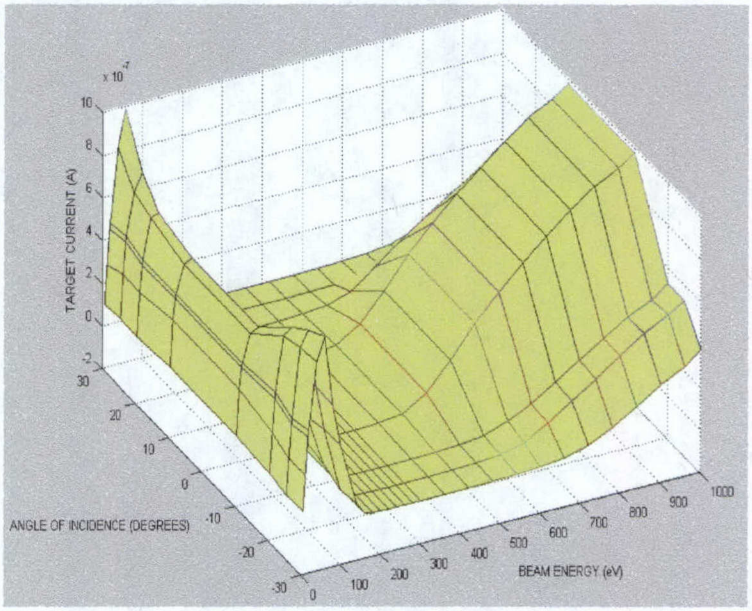

Figure 9. Target current of copper vs. beam energy and angle of incidence for clockwise and counter clockwise rotation of target.

Presented in Figure 10 is a plot of S.E.Y. (δ) vs. beam energy for a copper target at normal and oblique incidence. S.E.Y. is calculated using the expression: S.E.Y. = $1 - I_t / I_b$, where I_t is the target current and I_b is the primary beam current.

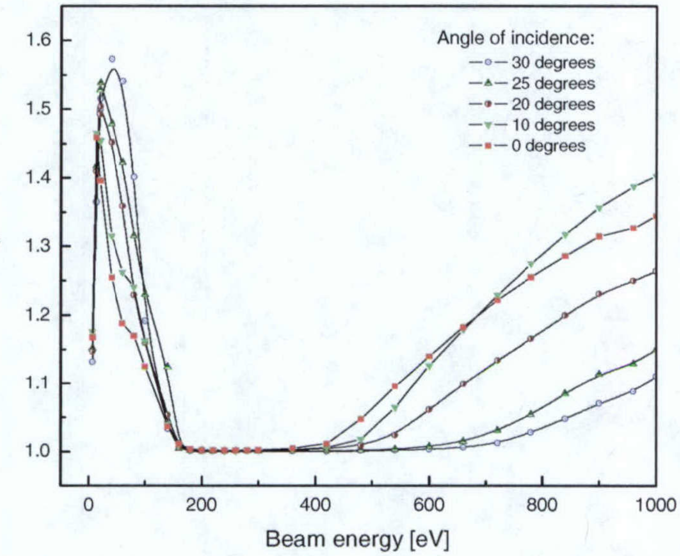

Figure 10. S.E.Y. δ of copper vs. beam energy for normal and oblique incidence of primary electrons.

The yield maxima in Figure 10 were recorded at about 60 eV. As expected, the maximum yield increases as the angle of incidence is increased from 0° to 30°. As primary electrons impinge on the target and penetrate it, they interact with the surrounding material generating secondary electrons. When the angle of incidence is nonzero ($\theta \neq 0$), the penetration depth of primary electrons is reduced by a factor of cos (θ), causing a larger number of secondary electrons to be emitted as compared with normal incidence [3,4].

D. Preliminary Heat distribution results in copper using ANSYS

As was indicated in last year's annual report, considerable variation in the S.E.Y. was observed as the DC beam was incident onto a sample over a period of time. To better understand this aspect of the problem, initial thermal simulations based on a simplified *two-dimensional* problem were performed. A heat source of 403 K was assumed at the center of the copper sample – over a 1 mm diameter area – and a temperature of 303 K was forced on the circumference. Appropriate parameters for conductivity and specific heat were given for copper. As expected, a radially symmetric temperature distribution was observed, as shown in Figure 11. The simulation was transient and a plot of the variation of temperature with time is indicated in Figure 12. It is observed that the temperature distribution reaches equilibrium within a short period of time, of the order of 40 – 80 s.

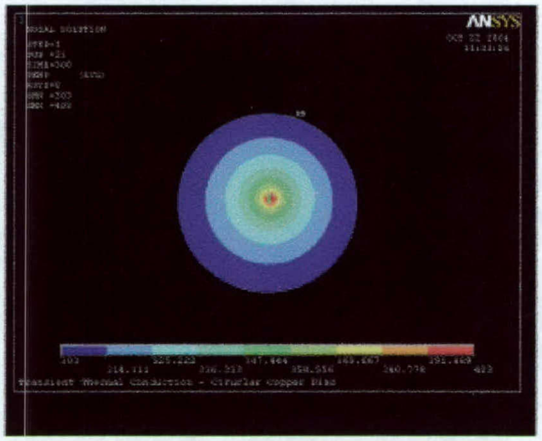

Figure 11: Contour plot of transient thermal conduction in a copper disc.

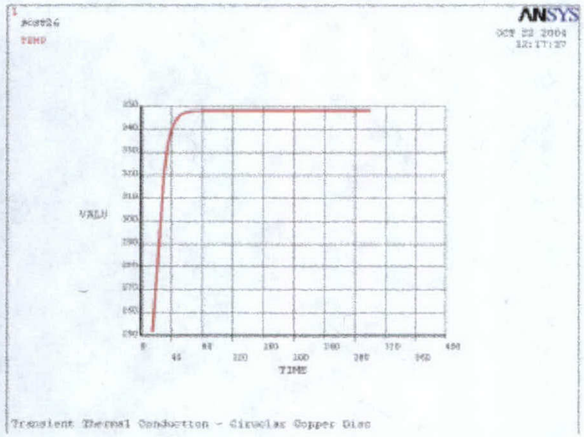

Figure 12: Graph of the transient thermal response of a copper disc.

Subsequent simulations focused on extending the previous results to the three-dimensional case along with the consideration of the more difficult thermal effect – radiation. In ANSYS, it is assumed that there is a space node that radiates to the sample, according to the Stefan-Boltzmann law. Again the simulations were simplified by considering that the top surface was the only one being irradiated. Temperatures of 100 K and 500 K were imposed on the ends of sample, while the radiating node was at a temperature of 1000 K. Figures 13 and 14 show the various stages in a 10 second simulation, wherein by the end, the sample reaches thermal equilibrium. The variation of radiation with time is indicated in Figure 15.

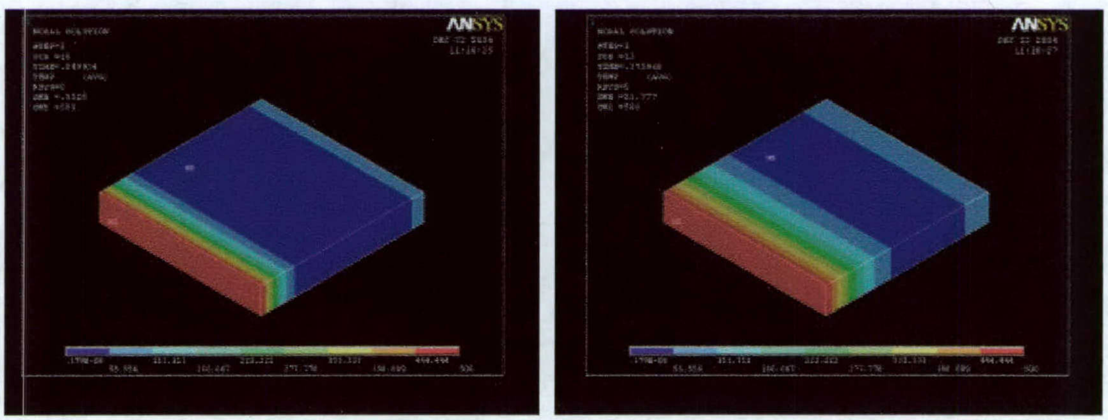

Figure 13. Various stages (increasing time) in a 10 second thermal simulation of a sample with 100 K (left) and 500 K (right) temperatures imposed at ends and top surface being radiated to by a node at 1000 K.

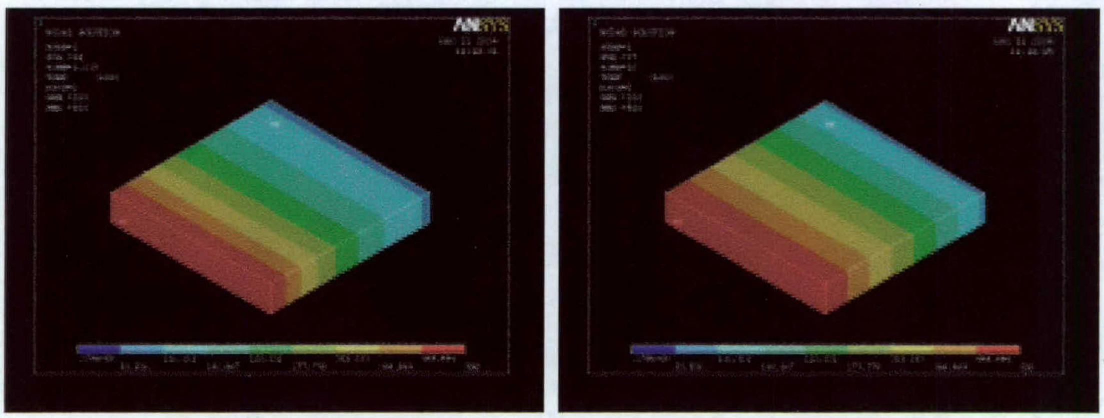

Figure 14. Various stages (increasing time) in a 10 second thermal simulation of a sample with (left) 100 K and (right) 500 K temperatures imposed at ends and top surface being radiated to by a node at 1000 K.

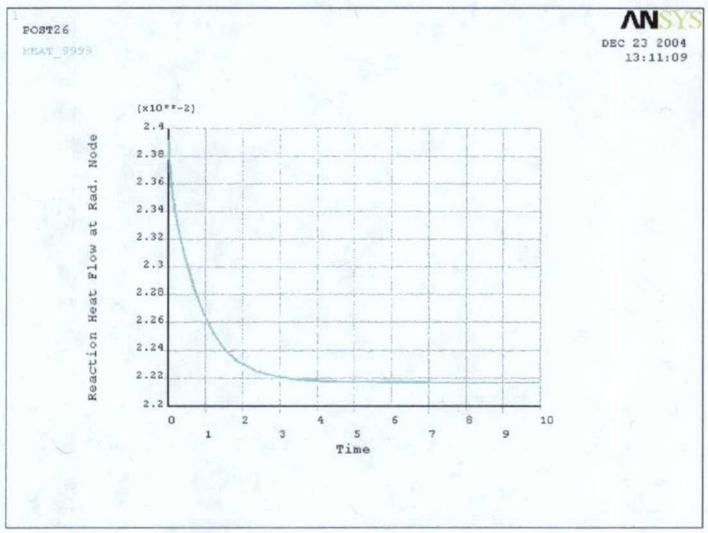

Figure 15. Variation of radiation with time (in seconds).

The final simulation (Figure 16) was performed because no expected observable (visual) gradients were noted on the top radiating surface. It turned out that the temperature of the radiating node had to be increased to an abnormally high value of 25000 K– approximately 250 times higher than the temperature on the sample – to observe the expected temperature gradients.

The thermal simulations were halted temporarily following the above case due to lack of enough experimental data and the fact that the results provided by ANSYS were contradictory to expectations, primarily the time scales, which were much shorter than expected.

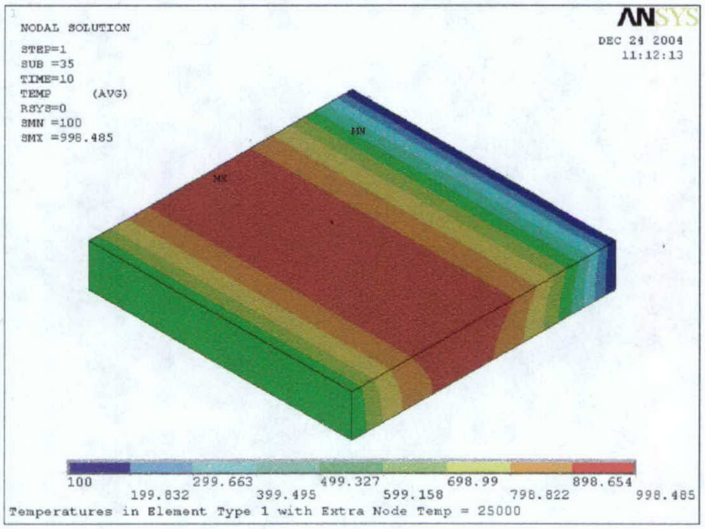

Figure 16. Gradients on top surface produced due to radiation by a node at 25000 K.

In experiments, the temperature of the copper sample was monitored *in situ* by placing a thermocouple on its edge. A temperature increase (from 27.4° C to 30.4° C) of approximately 3° C was measured while the beam energy was increased from 5 eV to 1000 eV, with a 1.525 A current flowing through the gun cathode. Using $\Delta T = 3°$ C, the incident thermal energy was estimated to be about 23 J, assuming negligible losses through radiation and conduction. This value is in very good agreement with that obtained for the energy input due to the incident electron beam - approximately 22 Joules.

Further investigation is needed to better understand the local conditions on the sample that is illuminated by the incident electrons.

Conclusions

The S.E.Y. yield and target current for copper have been measured (in DC mode) as a function of incident primary electron beam energy (6 eV to 1 keV) for both normal and oblique incidence. Initial temperature measurements on the edge of the copper target have been taken, and these results are being analyzed to consider what might influence the measured S.E.Y. The S.E.Y. values and shape are consistent with the literature, although the time-dependent behavior of the yield (S.E.Y. decreases over time at these low energies) is still under study.

Thermal modeling was performed for the copper sample using ANSYS 7.1. It is believed that the thermal effects prevalent on the sample are primarily due to local heating as in the case of lasers and other similar heat sources. It is therefore now assumed that it is beyond the capabilities of ANSYS to account for such effects, which is why other simulation software with capabilities for simulating the experimental conditions are being considered.

DC measurements of the S.E.Y. of a copper substrate plasma-sprayed with boron carbide are under way. The data will be recorded over the full range of the gun: 5 eV to 2 keV. The DC measurements will be followed by measurements in the pulsed regime for comparison. (These results will be presented at the 2005 IVEC Conference.)

Finally, in forthcoming experiments, a Nd:YAG laser will be used to ablate material from the various samples being studied to better understand the influence of microscopic surface morphology on S.E.Y. measurements.

The research effort will continue, thanks to a follow-on grant from AFOSR that commenced 1 January 2005.

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[2]Samples provided by L. Ives, Calabazas Creek Research, Inc., Saratoga, CA, USA (http://calcreek.com/index.html)

[3] R.O. Jenkins and W.G. Trodden, *Electron and Ion Emission from Solids, Secondary Emission of Electrons* (Dover, New York, NY, 1965), Ch. 6.

[4] A. Shih and C. Hor, "Secondary emission properties as a function of the electron incidence angle," IEEE Trans. Electron Devices, Vol. 40, No. 4, pp. 824-828, April 1993.

[5] V. Baglin, J. Bojko, O. Gröbner, B. Henrist, N. Hilleret , C. Scheuerlein, M. Taborelli, "The Secondary Electron Yield Of Technical Materials And Its Variation With Surface Treatments," Proceedings of EPAC 2000, Vienna, Austria.

IV. PERSONNEL, PUBLICATIONS, INTERACTIONS, AWARDS

PERSONNEL

Dr. Edl Schamiloglu	Professor and PI
Dr. Mark Gilmore	Assistant Professor and Co-PI
Mr. Nathan Zameroski	M.S. Student (graduated Dec. 2003, employed by Sandia National Laboratories)
Mr. Tengiz Svimonishvili	Ph.D. Student
Mr. Prashanth Kumar	M.S. Student
Dr. John Gaudet	Research Professor
Mr. Les Bowers	Research Scholar – providing computational support and interface with AFRL ICEPIC code

PUBLICATIONS

A. Journal Papers

1. N. Zameroski, T. Svimonishvili, M. Gilmore, E. Schamiloglu, and J.Gaudet, "Time-Dependent Secondary Electron Yield Measurements with Applications to Depressed Collectors," submitted to J. Vac. Sci. (2004).

B. Papers in Conference Proceedings

1. N. Zameroski, T. Svimonishvili, M. Gilmore, E. Schamiloglu, and J. Gaudet, "Measurements of Secondary Electron Yield from Materials with Application to Depressed Collectors, *Proceedings IVEC 2004*, (Monterey, CA, 2004), p. 150-151.

2. E. Schamiloglu, M. Gilmore, C. Watts, J. Gaudet, H. Bosman, T. Svimonishvili, P. Kumar,

and N. Zameroski, "Time-Dependent Secondary Electron Yield Measurements from Materials with Application to Depressed Collectors," to be published in *Proceedings IVEC 2005*, (Noordwijk, The Netherlands, April 2005).

C. Presentations

1. N. Zameroski, T. Svimonishvili, M. Gilmore, E. Schamiloglu, J. Gaudet, and M.O. Manasreh, "Secondary Electron Yield Measurements," Bull. Am. Phys. Soc. **48**, 312 (2003).

2. N. Zameroski, "Secondary Electron Yield Measurements for HPM Source Applications," poster presented at the Directed Energy Professional Society Annual Symposium

(Albuquerque, NM, November 2003).

3. A.D. Andreev, N. Zameroski, T. Svimonishvili, M.A. Gilmore, J.A. Gaudet, and E. Schamiloglu, "Monte-Carlo Simulations of Secondary Electron Emission Yield from Materials with Application to Depressed Collectors," *IEEE International Conference on Plasma Science* (Baltimore, MD, June 2004).

4. T. Svimonishvili, N. Zameroski, M. Gilmore, E. Schamiloglu, J. Gaudet, and L. Yan, "Characterization of Novel Materials with very low Secondary Electron Emission Yield for use in High-Power Microwave Devices," Bull. Am. Phys. Soc. DPP04, HP1.120 (2004).

INTERACTIONS

Nate Zameroski, Mark Gilmore and Edl Schamiloglu attended IVEC 2004 in Monterey. CA in April 2004.

Mark Gilmore and Edl Schamiloglu interacted with Dr. Lawrence Ives (Calabazos Creek Research), Dr. Baruch Levush (NRL), and Dr. Monica Blank (CPI) at ICOPS 2004 in Baltimore, MD, June 2004.

Dr. Diana Loree at AFRL authorized SAIC to purchase, on behalf of this UNM effort, a low energy electron gun in order to access the energy range of 5 eV – 1 keV.

The UNM team has been working closely with Dr. Keith Cartwright (AFRL) with the assistance of Mr. Les Bowers in improving the fidelity of the secondary electron emission models in ICEPIC.

RECOGNITION

Professor Edl Schamiloglu, 2004 ECE Lawton-Ellis Award. Professor Schamiloglu also chaired the HPM Subpanel of a National Academies Panel Assessing Directed Energy Testing Infrastructure, Fall 2003 and Spring 2004.

Professor Mark Gilmore is a recipient of a 2004 Department of Energy Young Investigator Award.

NEW DISCOVERIES, INVENTIONS, PATENTS

None.