On the Heating of a Field Ion Microscope Specimen

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ABSTRACT
The temperature distribution in a field ion microscope (FIM) specimen heated simultaneously by thermal radiation, the imaging gas, and an energetic beam of charged particles was calculated in the steady-state approximation employing a realistic model for the FIM specimen. The variation in the cross-sectional area of the specimen with distance along the beam was taken into full account. The possibility of a temperature change caused by the thermoelastic effect was also considered and shown not to be of importance. The value of \( \Delta T_{\text{max}} \) (maximum temperature difference along the length of the specimen) was \( \approx 1.8 \times 10^{-4} \) \( ^\circ \text{C} \) at the best image field (4.4 \( \times 10^{-4} \)) for tungsten imaged at 20\(^{\circ} \text{C} \) with helium gas. Hence, it was concluded that the use of observing a specimen by field ion microscopy did not perturb appreciably the temperature of the tip. It was also shown that a rather high energy density beam of energetic particles was required to produce a significant value of \( \Delta T_{\text{max}} \).

§ 1. INTRODUCTION
The use of the field ion microscope (FIM) for problems such as the direct observation of defects, description studies, fundamental experiments concerning image contrast, field evaporation, and field ionization requires an accurate knowledge of the temperature distribution in the specimen. In this present work we have calculated the steady-state temperature distribution in a FIM specimen heated simultaneously by thermal radiation, the imaging gas, and an energetic beam of charged particles. A realistic model for the FIM specimen was employed, and the variation in the cross-sectional area of the specimen with position along the specimen was taken into full account. In addition the possibility of a heating (cooling) effect...
during pulse field evaporation, caused by the thermomechanical effect was considered. The resulting expressions were applied to the recent experimental work of Scanlan, Styris, and Seidman (1973a, b, 1974a, b) on an in-situ FIM study of radiation damage in tungsten irradiated with 300 kev W ions, although the conclusions obtained are general.

§ 2. The Model

The FIM specimen was represented by the model shown in the figure. This model consisted of a cylinder of fixed radius \( r_0 \) in the region \( 1 \leq x \leq L_0 \), and a truncated cone in the region \( 0 \leq x < (L_0 - \delta) \). The cross-sectional area of the cone in region II was \( \pi r(x)^2 \), and the area of the circle at \( x = (L_0 - \delta) \) was equal to the area of a FIM tip \( \pi r_0^2 \). The FIM specimen had cylindrical symmetry about the \( z \) axis (see figure). It was assumed that the specimen was well clamped at \( z = 0 \) (i.e., the interface had a low thermal impedance), so that the beginning of the specimen at \( z = 0 \) was at the same temperature, \( T_0 \), as the heat sink (copper) to which it was attached. Further, it was assumed that the steady-state temperature conditions were achieved instantaneously. This latter assumption was reasonable in view of the small heat capacity of the specimen relative to the heat capacity of the heat sink to which it was fastened at \( z = 0 \).

![Diagram of FIM specimen](image)

Model of the FIM specimen employed for the calculations presented in § 3.

The problem to be solved was one in 1-dimensional heat flow which was governed by the steady-state differential equation

\[
K \frac{dT}{dx} + \frac{1}{c_p} \frac{dQ}{dx} + \frac{1}{\rho c_p} \frac{dT_0}{dx} = 0,
\]

where \( T \) is temperature, \( K \) is the thermal conductivity of the material, \( Q \) is the heat input \((\text{cal cm}^{-2} \text{ sec}^{-1})\), \( J \) is the total current step to the tip, \( \rho \) is the resistivity of the material, \( J \) is Joule's constant, and \( a(x) \) is the cross-sectional area of the specimen \( \left( \pi r(x)^2 \right) \). The first term in eqn. (1) was simply the rate at which an element of volume between \( z \) and \( z + dz \) gained heat by flow across the surfaces at \( z \) and \( z + dz \). The second term was the rate at which the surface area of this volume element received energy from thermal radiation, gas conduction and (or) an energetic beam of charged particles. Finally, the third term was the rate at which power was generated in this volume element due to the resistive (Joule) heating effect caused by the electrons which had tunneled through the imaging gas sheets into the metal. An exact calculation would have employed the Stefan-Boltzmann law for the heating effect caused by the thermal radiation. Unfortunately, the use of the Stefan-Boltzmann law resulted in a non-linear differential equation, hence we made the assumption of a constant \( Q \) which made the governing differential equation linear. This assumption implied that the expression that we obtained for \( \Delta T_{\text{max}} \) was a good estimate. In addition, both \( \rho \) and \( K \) were assumed to be constants independent of \( T \). This assumption was validated by the smaller calculated values of \( \Delta T_{\text{max}} \).

Equation (1) was solved in the two regions described in § 2. In region II \( [0, L_0] \), the quantity \( r(x) = x \) and eqn. (1) was integrated twice to find the temperature distribution \( T(x) \). In region II \( [L_0, L_1] \), the quantity \( r(x) = \left( \frac{L_0}{L_1} \right) x \) and \( \tan \alpha \), where \( \tan \alpha \) is equal to \( \left( \frac{L_0}{L_1} \right) \). To solve eqn. (1) in region II the differential equation was transformed according to the relationship \( r(z) \) to obtain

\[
\frac{dT}{dz} = -\frac{Q}{K \rho c_p} \left( \frac{1}{x^2} \right) - \frac{P_T}{K \rho c_p \tan \alpha} \left( \frac{1}{x^2} \right).
\]

Equation (2) is a second-order non-homogeneous linear differential equation with variable coefficients which could be solved by the variation of parameters method (see Sedyhinskii and Redheffer (1966)), since the solution to the homogeneous equation had two linearly independent

1 The distribution \( T(z) \) was given by a quadratic expression.
The four constants in $T_0(x)$ and $T_1(x)$ were determined from the following four boundary conditions:

\[
T_0(x=0) = T_1, \\
T_1(x=L_2) = T_0(x=L_1), \\
(\partial T_1/\partial x)|_{x=L_1} = - (\partial T_0/\partial x)|_{x=L_1}, \\
(\partial^2 T_0/\partial x^2)|_{x=L_2} = - (\partial^2 T_1/\partial x^1)|_{x=L_2}.
\]

where $\phi_{e}$ was the total flux (cal cm$^{-2}$ sec$^{-1}$) which entered the specimen at $x = L_2$. After the four constants were evaluated with the aid of eqns. (4) to (7) the value of $\Delta T_{\text{max}}[T(x=L_1-2)] - T(x=L_1)$ was calculated to be given by the expression

\[
\Delta T_{\text{max}} = \frac{\phi_{e}}{K} \frac{\tan \alpha}{\tan \alpha - \frac{L_2}{L_1}} \left[ \frac{1}{\tau_2} \frac{L_2}{\tan \alpha - \frac{L_2}{L_1}} \right] - \frac{1}{\tau_1} \left[ \frac{L_1}{\tan \alpha - \frac{L_1}{L_2}} \right] + \frac{2Q}{K} \left( \frac{L_1}{\tan \alpha - \frac{L_1}{L_2}} + \frac{L_2}{\tan \alpha - \frac{L_2}{L_1}} \right) \]

This general expression for $\Delta T_{\text{max}}$ is quite simple to handle, the value of $\Delta T_{\text{max}}$ is given by the sum of these terms, each of which is caused by a different source of energy input. The first term was $(\phi_{e}/K)$ times a geometric factor, and was the contribution to $\Delta T_{\text{max}}$ caused by the heat input which entered the surface of the FIM specimen at $x = L_2$. The second term had its origin in the reverse heating effect, and was given by $(P_{r}/K)$ times a geometric factor. The third term was $(Q/K)$ times a geometric factor, and originated with the thermal radiation, heat conduction, and charge exchange which contributed to the thermal equilibrium in the FIM specimen.

§ 4 THE HEATING (COOLING) OF THE FIM TIP AS A RESULT OF THERMOLASTIC EFFECT

It is well known (e.g. see Patton and Gurry (1939)) that the adiabatic elastic deformation of a solid is accompanied by a temperature change of the solid. This phenomenon is termed the thermelastic effect.

Adiabatic conditions the application of a compressive hydrostatic pressure produces a temperature increase, while a tensile hydrostatic pressure causes a temperature decrease. The adiabatic relationship between the temperature and the hydrostatic pressure ($P$) is

\[
\frac{\partial T}{P} = \frac{\rho}{c_p}
\]

where $\rho$ is the volume coefficient of thermal expansivity ($10^{-3}$), $c_p$ is the heat capacity (cal cm$^{-3}$ K$^{-1}$), and $P$ is in calories.

The technique of pulse evaporation offers a set of conditions under which the possibility of adiabatic stressing of the FIM tip arises. The stress on an FIM specimen has its origin in the electric field which is used both to image and field-evaporate the specimen. When a field evaporation voltage pulse is superimposed on the BHF the rise and fall time of the pulse is often in the low 10$^{-9}$ sec range, and with the advent of the atom probe/FIM time periods as small as 10$^{-9}$ sec are not uncommon. If the rise and fall times of these voltage pulses are small compared to the relaxation, time for achieving thermal equilibrium, then we have a change in pressure which has occurred adiabatically. To calculate this time we assumed that the FIM tip was stressed adiabatically, and that the mean temperature ($T$) of the region differed from that of the heat sink by an amount $T_{T_{\text{FIM}}}$ to $T_{T_{\text{FIM}}}$. The expression for the rate at which $T_{T_{\text{FIM}}}$ decays to $T_{T_{\text{FIM}}}$ in the sense is given by (Cardwell and Jaeger (1959))

\[
T_{T_{\text{FIM}}} = T_{T_{\text{FIM}}} - \frac{E_1 R}{\gamma E_1} \left( \frac{E_1 R}{E_1 R} \right) - \frac{E_1 R}{\gamma E_1} \left( \frac{E_1 R}{E_1 R} \right)
\]

From which it can be shown that an approximate relaxation time ($\tau$) for achieving thermal equilibrium is

\[
\tau \approx \frac{R^2}{K}
\]

Not only the tip region of the specimen was stressed, we took $K$ to be $10^9$. Employing the known values of $K$ and $c_p$ (deHaas and Wolfard (1938) and Johnson (1960)) it can be shown that $r(10^9) \approx 10^{-9}$ sec and $r(10^9) \approx 10^{-8}$ sec. Since these relaxation times were at least two orders of magnitude smaller than the shortest rise or fall time period employed in the pulse evaporation technique we concluded that this stress was adiabatic. Therefore, the thermelastic effect was not a source of a temperature change in the tip region of the FIM specimen.

§ 5 APPLICATION TO EXPERIMENT

We now consider the application of eqn. (8) for $\Delta T_{\text{max}}$ to experimental results which encompassed all the sources of heat input discussed in § 3. The experimental parameters employed were taken from the recent work of Seidman et al. (1976 a, b) though the specific conclusions are quite similar.
5.1 The Heating Effect during Observation of a FIM Specimen at Best Imaging Field (BIF)

The sources of heat input to the FIM specimen during observation at BIV were as follows:

1. A total flux of energy \( \phi T \) to the tip at \( r = (L_4 - 3) \) which was composed of the following four contributions:

   (a) A flux \( \phi_1 \) due to the transfer of kinetic energy from the imaging gas atoms to the surface of the specimen;

   (b) A flux \( \phi_2 \) caused by electrons which tunnelled into the FIM specimen from the imaging gas atoms at a value of energy greater than the Fermi energy;

   (c) A flux \( \phi_3 \) resulting from the conductive energy through the imaging gas inside the FIM;

   (d) A flux \( \phi_4 \) caused by the thermal radiation from surfaces at temperature greater than the temperature of the FIM specimen.

2. The resistive (Joule) heating caused by the tunnelled electrons after they have tunnelled into the specimen.

3. The contributions to \( Q \) from thermal radiation and conduction of energy through the imaging gas. These contributions entered the specimen over its entire surface area, except at the tip, i.e., the area at \( r = (L_4 - 3) \) as we have already considered the flux \( \phi \) which entered the specimen at \( r = (L_4 - 3) \).

4. Therefore, during imaging of a specimen at BIV, all the terms in eqn. (8) contributed to \( \Delta T_{\text{max}} \).

The fluxes \( \phi_1 \) and \( \phi_2 \) were calculated from the following relationships:

\[
\phi_1 = \eta_0 \phi T + \phi_E, \quad \phi_2 = \eta_0 \phi, \quad \phi_3 = \eta_0 \phi, \quad \phi_4 = \eta_0 \phi.
\]

where \( \eta_0 \) was the standard gas kinetic value of the flux, \( \phi \), was the enhancement factor (Southall 1953, 1965) due to the polarizability \( \psi \) of the imaging gas atom or molecule in the electric field \( E_T \) at the temperature of the imaging gas, and \( \phi \) was the average energy a tunnelled electron transferred to the specimen. The flux \( \phi \) was calculated from the standard gas kinetic expression (e.g. see White 1966) for conduction. The flux \( \phi_T \) was calculated from the Stefan-Boltzmann law taking the emissivity of the specimen to be \( \phi_0 \), and assuming that all the radiation which entered the specimen from \( r = (L_4 - 3) \) came from surfaces which were at 300 K.

The value of the flux \( \phi_1 + \phi_2 \) was \( 2 \times 10^{-5} \text{ cal cm}^{-2} \text{ sec}^{-1} \), with \( \phi_1 \) contributing less than \( 3 \% \) of the total. The calculation was made for the case of helium at a pressure of \( 10^{-4} \text{ Torr} \), with the specimen at a flux \( L = 4.4 \times 10^{-4} \text{ cm}^{-2} \). Since the energy distribution of helium close to the energy distribution of tunnelled electrons was used to determine the energy distribution of helium close to the energy distribution of tunnelled electrons, we used the data measured by Müller (1964) data (see fig. 7 in their paper) on the energy distribution of helium.

He was obtained by field ionization. These data indicated that \( \eta_0 = 1.5 \times 10^{-7} \text{ cal cm}^{-2} \text{ sec}^{-1} \).
was equal to $\Phi_i$, $\psi$ was equal to $\Phi$, plus the energy input to the specimen from the charged particle beam, and $I$ was equal to zero. In the case of the experiment of Sebestyen et al. (1970 a, b) the 200 keV ion beam delivered $3 \times 10^{-12}$ cal cm$^{-2}$ sec$^{-1}$ to the FIM specimen, so that the contribution to $\Delta T_{\text{max}}$ did not exceed $2 \times 10^{-3}$ K during the irradiation. Whereas, if the specimen was irradiated with a 2 meV particle at a current density of $5 \times 10^{-10}$ amp cm$^{-2}$ then $\Delta T_{\text{max}}$ would have been $1'$ K. Thus, we concluded that in order to produce significant values of $\Delta T_{\text{max}}$ during an irradiation it would be necessary to use extremely high-power beams.

§ 6. Conclusions

1. The exact steady-state temperature distribution along a FIM specimen was calculated employing a realistic model of a FIM tip. Full account was taken of the variation in cross-sectional area of the specimen with position along the length of the specimen.

2. The act of observing a FIM specimen at HF ($4.4 \times 10^{-4}$) in helium imaging gas at a pressure of $10^{-5}$ Torr and 150 K only caused a value of $\Delta T_{\text{max}}$ of $2 \times 10^{-12}$ (maximum temperature difference along the length of the specimen).

3. The use of imaging gases such as neon, argon, or hydrogen with polarizabilities greater than that of helium does not change the conclusion regarding the magnitude of $\Delta T_{\text{max}}$.

4. The process of field-evaporating a tungsten specimen does not produce an appreciable value of $\Delta T_{\text{max}}$.

5. Irradiation of a tungsten specimen with an ion beam which delivered $2 \times 10^{-2}$ cal cm$^{-2}$ sec$^{-1}$ only produced a value of $\Delta T_{\text{max}}$ of 8 $\times 10^{-3}$ K. To produce a $\Delta T_{\text{max}}$ of 1' K by irradiation with a beam of charged particles, it was necessary for the beam to have a power density of $10^2$ W cm$^{-2}$.

6. The question of the thermoelastic effect producing a $\Delta T$ in the tip region of the FIM specimen during pulse field evaporation was considered and shown not to be possible.

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References


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