

Stress-Dependent Contact Potential in Copper*

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We have measured the compressionally induced change in contact potential for the (100) face of a single crystal of copper. For a change in stress of about 34 atm we observed a negative contact-potential change which is interpreted as a decrease in work function. This change is $(-2.0 \pm 1.2) \mu\text{V}/\text{atm}$, which gives an equivalent gravitationally induced field of $(-1.8 \pm 1.0) \mu\text{V}/\text{m}$. The crystal face was cleaned by Ar^+ bombardment and measurements made at 2×10^{-8} Torr. Some experiments on polycrystalline copper in different environments are also reported. A simple calculation based on the Gordy equation as interpreted by Steiner and Gyftopoulos gives, for a stress applied along the [001] cube axis, an *increase* of the work function with stress of $4.3 \mu\text{V}/\text{atm}$ for the (100) face but a *decrease* of $3.8 \mu\text{V}/\text{atm}$ for the (110) face.

I. INTRODUCTION

Experiments of Witteborn and Fairbank¹ set up to measure the gravitational mass of the electron have initiated numerous investigations which are concerned with the sign and magnitude of the electric field induced by gravity just outside the surface of a free-standing metal. Table I is a listing of values of the gravitationally induced electric field as determined both experimentally and theoretically since that time. The Witteborn-Fairbank experiments imply an electric field in the direction of the gravitational field of order 5×10^{-11} V/m. Prior theoretical work by Schiff and Barnhill² predicted essentially this result. However, Dessler *et al.*³ pointed out that the gravitationally induced electric field inside a block of Cu should be of order 10^{-6} V/m and opposite to the gravitational force direction. This view is supported by several other investigators,⁴⁻⁷ who consider the shift of the conduction band and the change in density of conduction electrons with respect to pressure. Harrison⁸ points out that simple models of the surface give a resultant field outside of the same magnitude and direction as that inside (i.e., approximately 10^{-6} V/m). Herring⁴ indicates that a cancellation of body and surface fields in a region outside the metal to one part in 10^5 , which would be necessary to agree with the free-fall experiment, would be quite unlikely. The Witteborn-Fairbanks experiment implies that the work function measured at various heights outside a vertical cylinder supported at the bottom in a gravitational field is the same and that the compression at the bottom due to the weight of the cylinder has not changed the work function more than 5 parts out of 10^{11} . A variety of shielding mechanisms⁷⁻⁹ operating on the metal surface

have been proposed to account for this discrepancy between the Witteborn-Fairbank result and the shift in "inner work function" predicted by Dessler and others.

A problem similar to that above, but one which is more susceptible to experimental investigation, is the question of the change in work function with uniform compression. This effect has been measured for large stress by Beams,¹⁰ Craig,⁸ Craig and Radeka,¹¹ French and Beams,¹² and Cohen *et al.*¹³ If a rod under uniform compression experiences a shift in the work function $\delta\phi$, then the field just outside a vertical rod supported at the bottom in a gravitational field will be given by $\delta\phi/e\delta y$, where y is the vertical coordinate measured downward from the top of the rod. The stress S at any vertical point in the rod is given by $S = \rho gy$, where ρ is the density of the rod and g is the gravitational constant, so that $\delta S = \rho g \delta y$. Now since the experiments described above measure $\delta\phi/e\delta S$, it is easy to convert to the induced gravitational field relevant to the Witteborn-Fairbank experiment by $\delta\phi/\delta y = g\delta\phi/\delta S$. All of the compressional-stress experiments cited above are in general agreement with the predictions of Dessler *et al.*³ French and Beams¹² do, however, comment that the "oxide layers, moisture, impurities, etc., on the surface of a metal or alloy influence the measured contact-potential changes produced by tensile stresses." When the surface was free of moisture, oil, etc., and the experiment was performed in a nitrogen atmosphere, reproducible negative changes in contact potential with increasing tensile stresses were observed. At large *tensile*-stress levels, a value for Cu of $(+1.2 \pm 0.4) \mu\text{V}/\text{atm}$ was obtained. This would imply a gravitationally induced field

of $(+1.0 \pm 0.4) \mu\text{V}/\text{m}$.

Recent experiments with very low stress by Brown *et al.*¹⁴ give results for Cu of $(-0.03 \pm 0.15) \mu\text{V}/\text{m}$. Rieger,¹⁵ with a calculation utilizing electron-phonon interaction, obtains $+0.17 \mu\text{V}/\text{m}$. These results are in contrast to the predicted value of Dessler *et al.*³

In this paper we present results of stress-induced contact-potential change outside a (100) face of a copper single crystal under relatively clean surface conditions. Our stress of 34 atm is in an intermediate range between the experiments of Brown *et al.*¹⁴ and Craig.⁸ We use a straightforward dc technique and measure the stress-induced change in contact potential by monitoring the voltage on a fixed plate located just outside the metal surface. Our results show a negative voltage change in contact potential with compressional stress.

We interpret this negative change as a decrease in work function with increasing stress. A simple calculation based on the Gordy¹⁶ equation as interpreted by Steiner and Gyftopoulos¹⁷ gives an *increase* for the work function of the (100) face and a *decrease* for the (110) face with stress.

The change is of the same magnitude found experimentally.

II. EXPERIMENTAL

The single-crystal Cu sample used was of size $12 \times 5 \times 1$ cm. The rectangular faces of the single-crystal specimen were within $\frac{1}{2}^\circ$ of the [100] crystal direction. The mosaic spread as determined by elastic-neutron-scattering measurements is less than $20'$ of arc. The sample is rigidly held on the bottom of the chamber and on the top by the ram extension B (see Fig. 1). The sample A is guided by the top alignment support C, as shown. The stress is transmitted through the stainless-steel high-vacuum system by the bellows arrangement H. The circular capacitance plate I translates perpendicular to the face of the crystal and has a radius of 2 cm, the motion coupled into the system by the bellows H'. With the plate I in the maximum separation position, the wire-grid screen D allows both the sample A and plate I to be cleaned via argon-ion bombardment techniques. A Bayard-Alpert ion gauge was permanently attached to the system to monitor the pressure. The Cu sample was degreased, electrolytically

TABLE I. Summary of theoretical and experimental predictions of the gravitationally induced electric field outside of a vertical copper cylinder.

Experimental workers	Reference	$\delta\phi/e\delta y$ ($\mu\text{V}/\text{m}$)	Vacuum	Quality of cleaning
Witteborn and Fairbanks	1	-5.47×10^{-5}	10^{-11} Torr	No ultrahigh vacuum (UHV) cleaning; surface at 4.2 K so well covered
Craig	8	+4 to 6.4	Atmos.	Washed in alcohol
Beams	10	+1	10^{-5} – 10^{-6} Torr	No vacuum cleaning
French and Beams	12	$+1.0 \pm 0.4$	Atmos.	Noted significant effects due to different cleaning procedures
Brown <i>et al.</i>	14	-0.03 ± 0.15	Atmos.	None reported
Schumaker <i>et al.</i> (110)	21	-7	$<10^{-10}$ Torr	UHV heating
This work (100)		-1.6 ± 1.0	2×10^{-8} Torr	Ar* bombardment (300°C high-vacuum bake)
Theoretical workers	Reference	$\delta\phi/e\delta y$ ($\mu\text{V}/\text{m}$)		Theoretical model
Schiff and Barnhill	2	-5.6×10^{-5}		Shift due to gravity acting on a electron gas
Dessler <i>et al.</i>	3	+0.6		Shift due to gravity acting on the crystal lattice
Rieger	15	+0.17		Shift due to gravity acting on the lattice including electron-phonon interactions
This work (100)		+3.6		Semiempirical but includes surface-compression effects
(110)		-3.2		

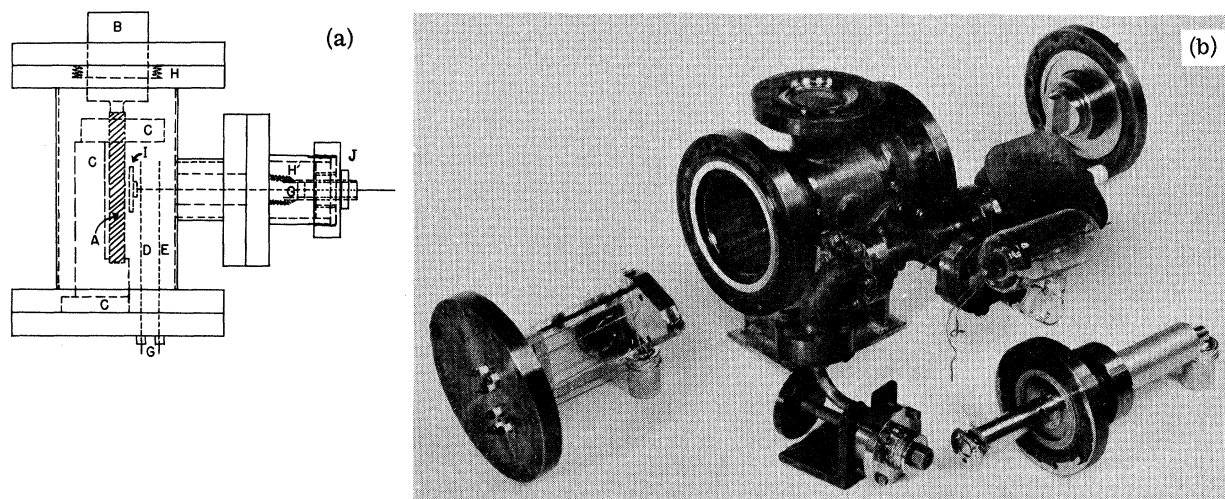


FIG. 1. (a). Mechanical details of experiment. A is the copper sample; B is the ram extension; C is the copper-sample holder; D and E are the argon-iron-bombardment grid and filaments, respectively; G are ceramic feed throughs; H and H' are stainless-steel bellows; I is the capacitor pickup plate; and J is the capacitor-crystal separation adjustment. (b) Sample chamber partially disassembled.

polished, ultrasonically cleaned, and inserted into the sample chamber. The apparatus was baked at 300°C for 8 h at a pressure of 10^{-5} Torr. This was followed by 2 h of Ar^+ bombardment at 400 eV and $30\ \mu\text{A}$. The system was sealed (at about 2×10^{-9} Torr) from the gas-handling manifold by a bellows-sealed ultrahigh-vacuum bakeable valve. The manifold side of the valve was then disconnected so that the work chamber could be moved to the press. During the transfer (a time of 1 h) but after turning the ion pump on, the vacuum had decreased to 2×10^{-8} Torr. The vacuum remained at this value for the course of the experiment. A shop-grade polycrystalline Cu sample was also used but a leak developed and the run was made at a vacuum between 10^{-5} and 10^{-6} Torr. A 4-ton ram (maximum force) was controlled by an electrically operated hydraulic pump and the pressure was read on the low-pressure side by a 0–10 000-psi Heise gauge. A 1-psi Heise-gauge reading corresponded to a ram force of 1 lb.

The electrical measuring circuit is shown in Figs. 2(a) and 2(b). The external resistance R gave the Keithley electrometer a time constant of about 6 sec. The system was calibrated for each sample-capacitor-plate separation d by putting a known (usually 0.301 mV) potential difference between the sample and pickup plate and observing the electrometer deflection. In this case, the small potential difference is measured by a potentiometer. V_B is a variable voltage which changes the contact potential difference between the stainless-steel pickup plate and the sample. This was monitored to three significant figures by a digital voltmeter.

A 3-mm-thick Pb sheet was inserted between the ram and ram extension. Compressional stress was normally cycled between 130 and 164 atm during data runs. The set pressure of 130 atm and the Pb

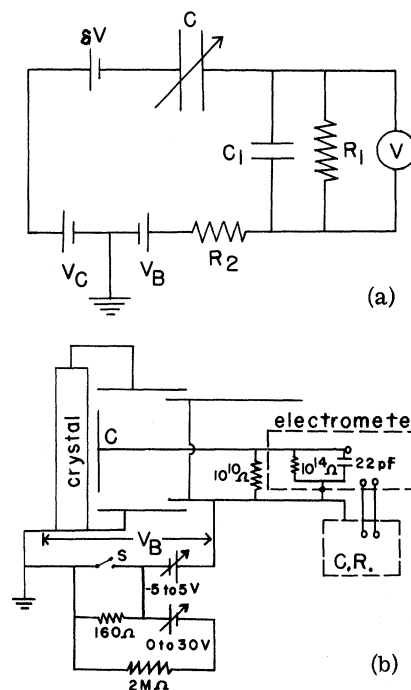


FIG. 2. (a) Basic electrical circuit of experiment. V_C , δV , and C are intrinsic components of the experiment while V_B , R_1 , R_2 , C_1 , and V are actual electronic components. (b) Actual electrical circuit of experiment.

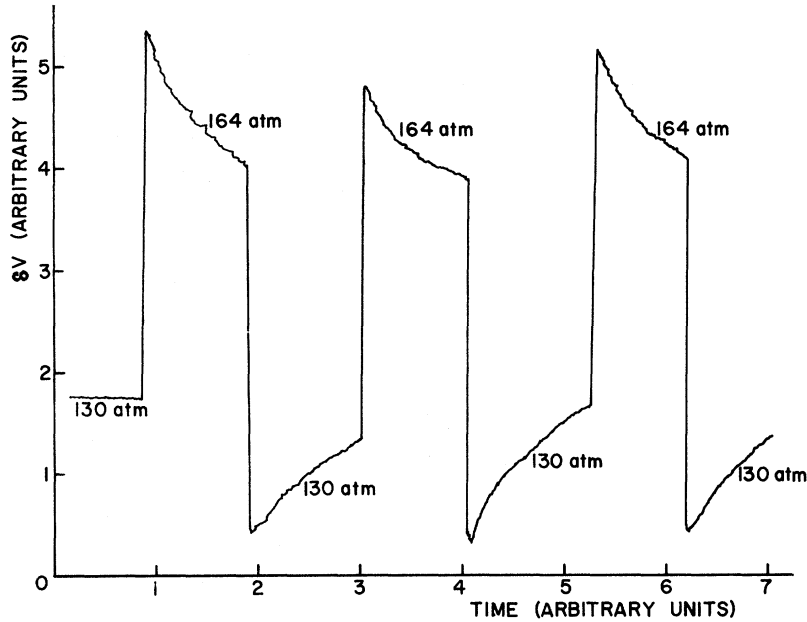


FIG. 3. Example of data obtained for pressure cycling between 130 and 164 atm. The time between pressure changes was not enough for all the charge to leak off the electrometer. The average of these data points gives a single point on Fig. 4.

sheet assured that any motion of the sample as a function of pressure was reproducible for the run.

III. DATA

Approximately 15–20 experimental data points were required to obtain a value for the change in contact potential due to stress. A run consisted of the following procedure repeated for three or four different sample–capacitor–plate separations d : First, the electrometer was calibrated by placing a known potential difference between the sample and the pickup plate. Next, for a given bias voltage V_B , the stress is cycled 8–10 times and the induced voltage recorded on a strip-chart recorder which monitored the output of the electrometer. A typical recorder chart is shown in Fig. 3. A value of δV is obtained from the jump of the voltage trace when the pressure is changed. The charge then leaks off the electrometer with a time constant $RC \sim 6$ sec. The voltage jump is independent of the time over which the change in stress is applied provided this time is less than 1 sec. For values of $V_B = V_c$ the induced voltage change was linear with stress and independent of the set pressure (usually 130 atm). All experiments were within the Hooke's-law region of stress.

Data similar to that of Fig. 3 are obtained for V_B values from -2.0 to $+1.5$ V in steps of 0.5 V. Typical data of V_B vs δV obtained in this manner are shown in Figs. 4 and 5. In the absence of fringing field the potential $V_{(Cu)}$ (acting in the gap) will be

$$V_{(Cu)} = \frac{\epsilon_0 q d}{A}, \quad (1)$$

where ϵ_0 is the permittivity of free space, q is the total charge, d is the sample–pickup-plate separation, and A is the effective area of interaction. All units are in the MKS system. The potential $V_{(Cu)}$ is positive on the Cu sample with respect to the pickup plate.

Now if we consider a simple circuit of a battery V_B with its positive pole connected to the pickup plate and its negative pole connected to the copper sample, the potential in the gap will satisfy the relation

$$-|e|(V_B - V_{(Cu)}) = \varphi_2 - \varphi_1. \quad (2)$$

φ_2 and φ_1 are the work functions of the pickup plate and Cu sample, respectively. Thus,

$$\left(\frac{\varphi_2 - \varphi_1}{e}\right) + V_B = \frac{\epsilon_0 q d}{A}. \quad (3)$$

If a stress is applied to the crystal, Eq. (3) will change by

$$-\frac{\delta\varphi_1}{e} = \frac{\epsilon_0(d\delta q + q\delta d)}{A}.$$

Now the electrometer can only measure the change in potential $\delta V_{(Cu)}$ due to the change in charge δq , i. e.,

$$\delta V_{(Cu)} = \frac{\epsilon_0 d \delta q}{A},$$

so that

$$\delta V_{(Cu)} = -\left(\frac{\delta\varphi_1}{e} - \frac{\epsilon_0 q \delta d}{A}\right),$$

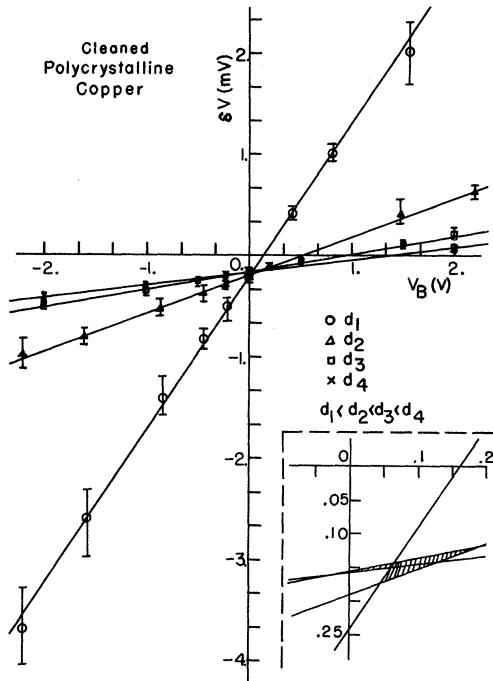


FIG. 4. V_B vs δV for polycrystalline copper sample. The insert is an enlargement of the region where the straight lines intersect.

and combining this with Eq. (3) gives

$$\delta V_{(\text{Cu})} = -\left(\frac{\delta\phi_1}{e}\right) + (V_c - V_B) \frac{\delta d}{d},$$

where $V_c = (\phi_1 - \phi_2)/e$. An increase in potential at the Cu sample corresponds to a decrease in potential at the electrometer pickup plate. Hence for the electrometer reading δV we obtain

$$\delta V = \frac{\delta\phi_1}{e} + (V_B - V_c) \frac{\delta d}{d}. \quad (4)$$

Corrections for fringing fields which depend upon the distance from the Cu surface, say, $E = E_0 - \epsilon_1 x$, have been calculated and are approximately $\frac{1}{2}\epsilon_1 \delta d$, which is of second order and thus neglected. Although we have minimized δd , we have found it impossible to eliminate the second term in Eq. (4). However, to obtain a value for $(\delta\phi_1/e)$, we need only to set $V_B = V_c$. We do this experimentally by changing the separation d and plotting δV vs V_B as in Figs. 4 and 5. Since the curves have different slopes they should intersect at only one point, namely, where $V_B = V_c$. At this point $\delta\phi_1/e$ and V_c may be obtained. The enclosed area of the three or four intersecting lines is an indication of the uncertainty in the values obtained. Each set of data was fit to a straight line by a least-squares calculation. The best values of $\delta\phi_1/e$ and V_c were found by averaging the inter-

sections of different pairs of lines. Alternately, we could plot δV vs $1/d$ for constant V_B . The δV intercept of these curves should be $\delta\phi_1/e$.

The stainless-steel pickup plate is not exactly parallel to the sample surface. This plus the possibility that different parts of the sample surface have different work functions ("patch effect") led Craig and Radeka for a similar geometrical arrangement to consider a simple model of two parallel capacitors, each with a different potential. In their Kelvin-probe method the predictions of this model are experimentally manifested by the dependence of the bias voltage for a null signal on the sample-pickup-plate distance. However, in our experiment we do not observe this effect; i. e., we do not observe departures from Eq. (4). In Fig. 6 we plot δV vs $1/d$ for the data shown in Fig. 4. The initial distance was difficult to measure when the experiment was in progress; the curves shown are for this initial value set equal to 0.035 cm. The displacement δd is calculated from the slopes of the curves to be, in this case, 0.38×10^{-4} cm. Elastic theory predicts the motion to be $\sim 0.14 \times 10^{-4}$ cm. It appears that we observe a slight motion of the sample not due to elastic compressional effects.

A time history of the result for $\delta\phi/e$ is given in Fig. 7. A very definite trend in $\delta\phi/e$ with time is seen on a time scale of several weeks. At present, there is no good explanation for the shifts portrayed in these figures. Possible explanations are surface contamination building up, implanted argon desorbing from the surface, oxidation of the copper surface, metallurgical changes within the crystal as a result of the stress cycles, and surface dif-

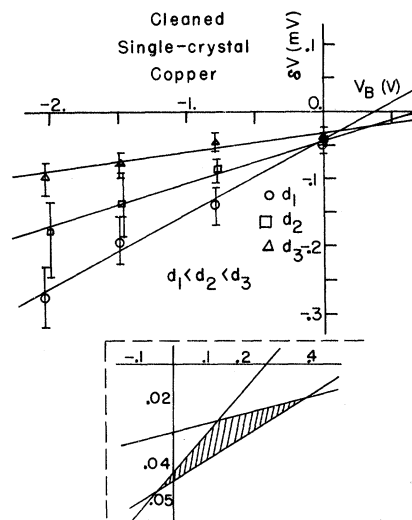


FIG. 5. V_B vs δV for single-crystal copper sample. The insert is an enlargement of the region where the straight lines intersect.

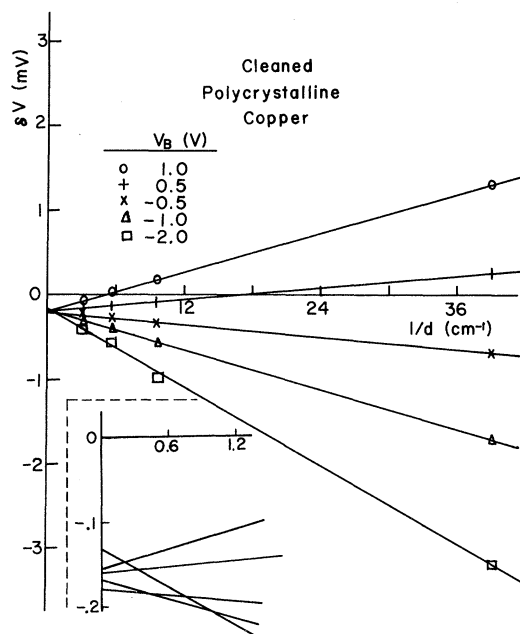


FIG. 6. δV vs $1/d$ for the data of Fig. 4. The insert is an enlargement of the region where the straight lines intersect.

fusion. The first of these explanations seems unlikely since most shifts due to contaminants occur within the first few monolayers, which would have formed, at 10^{-8} Torr, in about 5 min, i. e., on a much faster time scale than portrayed in Fig. 7. The second explanation would imply that the presence of argon interfered with the measurement and that the depletion of Ar from the surface in time gave rise to larger effects. One explanation for the fact that the vacuum was a factor of 10 worse after separation from the manifold is that the argon was slowly reemitted by the bombarded regions but poorly pumped by the ion pump. This observation supports the second explanation but is by no means conclusive. Another more likely explanation for the deterioration of vacuum is the opening for a leak during the moving of the work chamber to the press. The presence of a small leak would allow a continual source of O_2 which would interact with copper to form a copper-oxide layer whose formation rate was limited by the diffusion rate for Cu and O_2 through the previously formed CuO layer. The fourth explanation is postulated on the basis that microcreep and work-hardening phenomena have been observed in pure single crystals of copper at very low stresses, but the effect that might have on our measurement is unknown. A fifth possibility is that contaminants on the edges and back of the crystal might diffuse around to the Ar^+ -cleaned region on a time scale of this magnitude.

Because of the inconclusiveness of these explanations and the fact that most of these arguments lead to a deterioration of the quality of the measurement in time we have extrapolated our $\delta\phi/e$ values to $t=0$ for our best estimate of $\delta\phi/e$. Our extrapolation is via a least-squares fit to a straight line. One might argue that the effect has saturated after about 15 days and thus a better extrapolation is obtained by omitting the point at 31 days or fitting some polynomial to the data. This would lead to a much smaller value of $\delta\phi/e|_{t=0}$. We are reluctant to make such an extrapolation without a better basis for doing so.

Values for the shop-grade polycrystalline Cu in an atmospheric environment ranged from -2 to $+5$ $\mu V/atm$. By heating the sample in air it was possible to vary the contact-potential change by an order of magnitude but with such random fluctuations that no repeatable effects were observed. The polycrystalline sample cleaned by Ar^+ bombardment but in 10^{-8} Torr gave a value of $\delta\phi/e$, extrapolated via a straight-line fit to $t=0$, of (-0.4 ± 2.5) $\mu V/atm$.

The contact-potential difference V_c , which can also be determined from Figs. 4 and 5, is $(+0.15 \pm 0.20)$ V for the single-crystal run at 2×10^{-8} Torr, which means that the work function of our (100) face of copper exceeded the work function of the stainless-steel plate by about 0.15 V.

IV. DISCUSSION

Our results of (-1.8 ± 1.0) $\mu V/m$ do not agree with the estimates of Dessler *et al.* and others. If

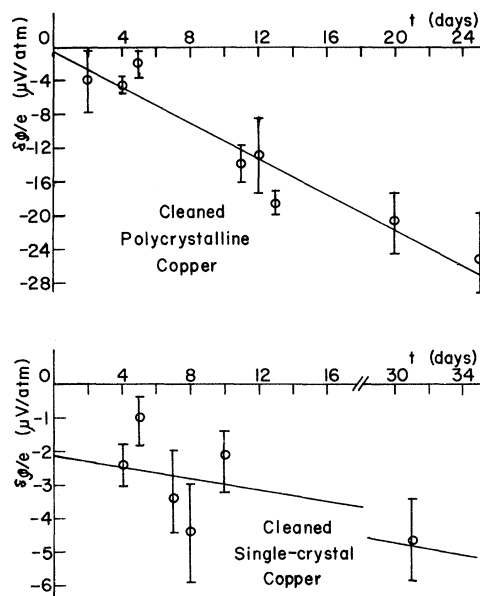


FIG. 7. $\delta\phi/e$ vs time after argon-ion bombardment for polycrystalline and single-crystal copper samples.

we attribute Dessler's estimated field to the shift in "inner work function" of the metal, then our results require a surface contribution of $(-2.8 \pm 1.0) \mu\text{V}/\text{m}$.

A theory which describes the clean-surface work function of crystallographic surfaces of single crystals has been developed by Steiner and Gyftopoulos.¹⁷ Their development is based on a re-interpretation of an equation initially proposed by Gordy.¹⁶ Specifically, the work function φ is given by the relation

$$\frac{\varphi}{e} = 0.98 \left(\frac{V_s + 1}{V_m} \right) + 1.57 \text{ V} , \quad (5)$$

where V_s is the surface valence or the number of electrons per surface atom which participate in bonding and r_m is the effective radius of the surface atom in angstroms.

If the interatomic separation in the bulk lattice between atoms is R_a (nearest neighbor) and R_b (next-nearest neighbor), the associated fractional bond numbers n_a and n_b satisfy the empirical relation given by Pauling¹⁸:

$$R_b - R_a = 0.26 \ln(n_a/n_b) . \quad (6)$$

The relation between the metallic valence V_m and the fractional bond numbers for atoms in the bulk is $V_m = 12n_a$. Normally only the 12 nearest neighbors are considered for the face-centered-cubic lattice. It is a straightforward procedure to calculate the change in V_s for a compressional stress. If we assume the changes in r_m and V_m to be negligible, then $\delta\varphi/e$ (in $\mu\text{V}/\text{atm}$) may be obtained for different crystal faces. Values for Cu parameters are given in Refs. 19 and 20. For a (100) surface

$$\left(\frac{\delta\varphi}{e} \right)^{(100)} = 0.98 \left(\frac{V_s}{V_m} \right) \left(\frac{x}{12} \right) , \quad (7)$$

while for a (110) surface

$$\left(\frac{\delta\varphi}{e} \right)^{(110)} = -0.98 \left(\frac{V_s}{V_m} \right) \left(\frac{2x}{21} \right) . \quad (8)$$

The quantity x is obtained from the relation $x = (n_a/n_b) - 1$. For a stress of 1 atm along the (001) cube axis, $x \sim 0.020 \times 10^{-3}$ and

$$(\delta\varphi/e)^{(100)} = +4.3 \mu\text{V}/\text{atm} ,$$

while

$$(\delta\varphi/e)^{(110)} = -3.8 \mu\text{V}/\text{atm} ,$$

where (100) and (110) crystal axes are perpendicular to the axis of compression. Thus, this simple model gives the same order of magnitude as that found experimentally, but depending on the

surface chosen predicts either an increase or decrease in work function with stress. A decrease in work function with stress for a clean (110) surface at the center of a polycrystalline Cu sample was reported recently by Schumacher *et al.*²¹ Their result is in agreement with the prediction of our Eq. (8).

Since the experimental crystal surface was only etched after its initial growth, our surface was obviously not a pure atomic (100) plane. The surface appeared bright to the eye but much surface roughness was apparent on close inspection. While one might expect the surface to average out with a value approximating that of (100) surface, since that was its x-ray orientation, it is possible that the surface was faceted (submicroscopically) to expose some other plane, such as a (111) or (110).

V. CONCLUSIONS

The negative voltage change with pressure of order $(-2.1 \pm 1.2) \mu\text{V}/\text{atm}$ measured on a cleaned (100) Cu face corresponds to a decrease in work function. We think our results are indicative of the (100) Cu surface. However, it is possible that the microscopic structure of the surface may not be (100). Also, there are argon ions on the surface due to our cleaning technique. The potential change could be caused by bowing of the surface. This bowing appears to be the same order of magnitude as that obtained by elastic effects. We feel that the surface roughness, the argon and other contaminating atoms on the surface, and the possible "bowing" of the sample do not appreciably change the extrapolated value of $\delta\varphi/e$. Our results are in disagreement with the predictions of our Eq. (7).

In the case of a free-standing metal our results give an electric field in the same direction as that found by Witteborn and Fairbank, but about 10^5 larger in magnitude. A more extreme extrapolation of our data to $t=0$ includes the Witteborn-Fairbank result as a possibility. Measurements on a polycrystalline Cu block under atmospheric conditions gave values of $\delta\varphi/e$ which are normally positive with compressional stress and which varied in time in an irregular manner, which points to the need for well-specified surface conditions. It seems that for clean-surface conditions the work function of (100) and (110) Cu decreases with compressional stress. However, it appears that a surface "shielding mechanism" was operable not only in the Witteborn-Fairbank experiment,¹ but also in other experiments.⁸⁻¹³ It also appears that very careful clean-surface techniques will be required to clarify the differences between the various experiments.

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Low-Energy-Electron-Diffraction Rotation Diagrams for the (100) Face of Aluminum*

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Low-energy-electron-diffraction rotation diagrams are calculated for Al(100), and the results are compared with experimental measurements. The agreement between theory and experiment is qualitatively correct for an energy $E=50$ eV and an angle of incidence $\theta=32^\circ$ but is much less satisfactory for $E=20$ eV and $\theta=50^\circ$. The effect of small changes in the upper-layer spacing on the calculated rotation diagrams is also investigated. It is found that the primary effect is to change the magnitude of the rotation diagram and not its qualitative shape. This apparent insensitivity to geometrical effects may be an asset in using the rotation diagrams to study resonance effects.

I. INTRODUCTION

Rotation diagrams (intensity vs azimuthal angle for fixed energy and polar angle) provide a unique test of the dynamical characteristics of model calculations of low-energy-electron-diffraction (LEED) intensities. Unlike LEED energy profiles (intensity vs energy for fixed polar and azimuthal angles) where interference effects between kinematic scattering events can produce major features,¹ in the absence of surface imperfections all structure in the rotation diagrams is due to either multiple-scattering effects or resonance effects.²⁻⁵ Recently there have been several experimental measurements and theoretical analyses of LEED rotation diagrams for Al(100) which emphasize the usefulness of the rotation diagrams for studying the effects of the surface potential barrier.⁶⁻⁸ A possible complicating feature in analyzing the experimental measurements would be undue sensitivity to small uncertainties in the surface geometrical parameters. In the present paper we show that

this is not the case by investigating the effect of small changes in the upper-layer spacing on the calculated rotation diagrams. The changes that are produced are more in the nature of an overall normalization change. This is in contrast to the large qualitative changes produced in the calculated LEED energy profiles by small changes in the surface geometrical parameters.⁹

The model used in the present work is the same as used previously by Laramore and Duke^{9,10} to analyze experimental energy profiles for the (100), (110), and (111) faces of aluminum. The model allows for refraction, but not reflection, of the electron wave field at the surface; and thus, includes resonances associated with the threshold conditions for the emergence of new beams but not those resonances associated with scattering into surface states. The effect of the surface-state resonances would be to produce local "maxima-minima structures" of the Breit-Wigner form in both the energy profiles³⁻⁵ and rotation diagrams.⁶⁻⁸ It is interesting to note that the model

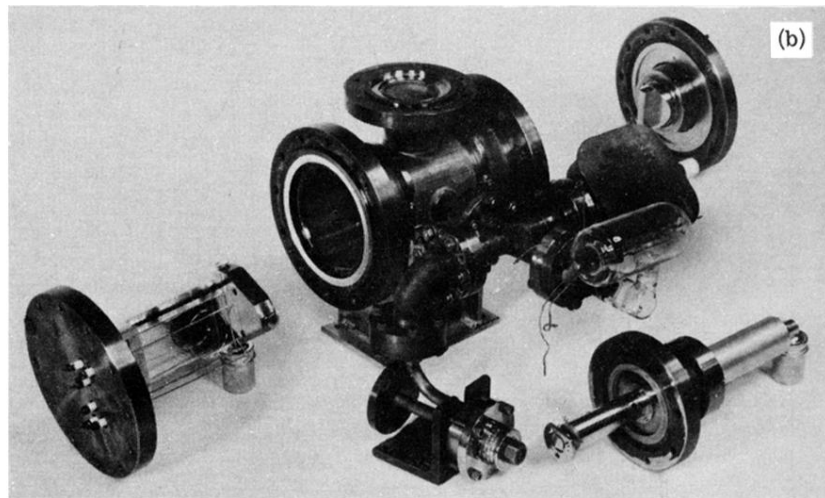
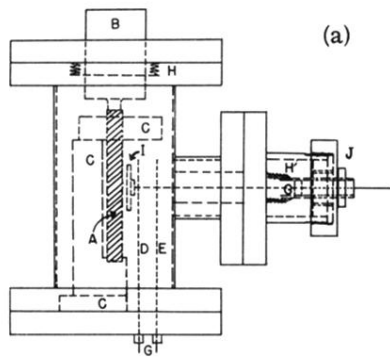


FIG. 1. (a). Mechanical details of experiment. A is the copper sample; B is the ram extension; C is the copper-sample holder; D and E are the argon-iron-bombardment grid and filaments, respectively; G are ceramic feed throughs; H and H' are stainless-steel bellows; I is the capacitor pickup plate; and J is the capacitor-crystal separation adjustment. (b) Sample chamber partially disassembled.