ceptibility curve, and in particular, a lifting of the curve of χ''. Such an effect is apparent in the experiments of Wijn[1] and Brown,[2] and the latter measurements were carried out to a frequency high enough so that one can be sure there is no microwave peak present. In the absence of any theoretical or experimental justification, however, these speculations must remain very tentative.

I am grateful to Fielding Brown and J. Kenneth Moore for communicating to me the results of their measurements and calculations, and for making many contributions to the work presented here.

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Effect of Strong Electrostatic Fields on the Resistance of Tungsten Wires in High Vacua

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The effect of a radial electrostatic field upon the resistance of tungsten in high vacua was reinvestigated employing lower pressures and better vacuum technique than in the original experiments of Worthing *et al.* Wires of 0.004-in. and 0.00045-in. diameter were subjected to negative and positive fields (retarding or assisting respectively electron motion from filament to plate) up to 9.0×10^6 and 1.4×10^6 volts/cm, respectively. The resistance abruptly decreased upon application of the electric field, increased slightly with time while the field was constant, and increased abruptly upon removal of the field regardless of the direction of the field. The abrupt increase was usually somewhat less than the abrupt decrease. The abrupt resistance changes satisfied the equation $\Delta R=\alpha E^{\frac{1}{2}}$, where ΔR is resistance change, E is applied field in volts/cm$\times10^{-6}$, and $\alpha=0.46$. A large part of the small resistance change with constant field was due to an observed filament temperature increase resulting from bombardment by the electronic portion of the observed ion-, photo-, and field-emission current. It was found that the photo and ion currents were much larger than the field-emission currents. No observable electrostatic effect was found which could account for the abrupt resistance changes. It has not been possible to offer a theory for the observed effects.

INTRODUCTION

THE effect of a radial electrostatic field upon the resistance of tungsten wires in high vacua was reinvestigated, with lower pressures and better vacuum techniques than in the original experiments.[1–3]

Worthing[1] observed that in the absence of the electric field, the resistance of a hot (2500°K) tungsten filament increased as expected because of the evaporation of the filament. Upon application of electric field strengths greater than about 0.5×10^6 volts/cm, he observed that the resistance abruptly decreased and simultaneously the time-rate of increase of resistance became less than for the no-field case. Estabrook,[2] employing molybdenum filaments at temperatures of 1462 and 1644°K, observed an abrupt increase in resistance upon application of the field along with a lessening of the time-rate of increase of resistance due to evaporation. Vissat,[3] employing tungsten in the temperature range 293°K to 853°K, observed an abrupt increase in resistance upon application of the field, agreeing with Estabrook but not with Worthing. He did not investigate the time rate of change of resistance. In each of these experiments the electric field was applied in cylindrical geometry with the filament positive with respect to the surrounding plate so as to inhibit electron emission from the filament. The pressures ranged from 10^{-5} to 10^{-6} mm Hg obtained with dynamic vacuum systems containing waxed joints. The systems probably were not very well outgassed. The filaments were dc heated, resulting in dc etch[4] of the surfaces and consequently the calculated electric field strengths were inaccurate. (Worthing and Estabrook employed Wimshurst machines as high-voltage sources for their fields.)

There appear to be only two theoretical papers concerning this effect.[5,6] Greibach[5] examined the problem from the thermodynamical point of view and was able to obtain qualitative agreement with Worthing but his calculated values for the resistance changes were but 1 percent of Worthing's experimental values. He attributed this to his assumption of an ideal filament surface, perfectly smooth and clean. Reid,[6] from kinetic theory, supported Estabrook[2] and by proper choice of parameters was able to obtain good agreement with Estabrook's measured resistance changes. However, Vissat's results[3] disagreed with Reid's predictions for tungsten.

In the present investigation, with improved experimental apparatus and technique, more complete information has been obtained concerning the effect of strong

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* Now at Jackson and Church, Saginaw, Michigan.

[1] A. G. Worthing, Phys. Rev. **17**, 418 (1921).

[2] G. B. Estabrook, Phys. Rev. **63**, 352 (1943).

[3] P. L. Vissat, Phys. Rev. **64**, 119 (1944).

[4] C. Herring and M. H. Nichols, Revs. Modern Phys. **21**, 185 (1949), p. 99 ff. See also D. B. Langmuir, Phys. Rev. **89**, 911 (1953).

[5] E. H. Greibach, Phys. Rev. **33**, 844 (1929).

[6] W. P. Reid, Phys. Rev. **63**, 359 (1943).

electrostatic fields on the resistance of tungsten. Additional insight into the complex nature of the effect is thereby obtained but a complete explanation of all observations is still lacking.

EXPERIMENTAL

The improvements over previous investigations were primarily in the vacuum techniques and high-voltage source for the field resulting in lower pressures, cleaner filaments, and steadier electric fields. The apparatus here used consisted of an electronic power-supply for the electric field, the experimental wires sealed into evacuated glass tubes, and the circuit for measurement of the changes in the resistance of the wires.

The high-voltage source was a half-wave rectifier power-supply (Fig. 1). Because the load current in the experiments is negligible, it was decided that electronic regulation with its accompanying transients would be a liability rather than an asset. With the circuit of Fig. 1, and a maximum current of 1.0 ma through the resistor R', the ripple factor was less than 0.035.

Three experimental tubes were used in this investigation. In the first tube a 0.004-in. tungsten filament wire and a tantalum cylindrical plate (8-cm length, 2-cm diameter) were used for the preliminary experiments which, though not described in the present report, yielded essentially the same results as the final experiments.

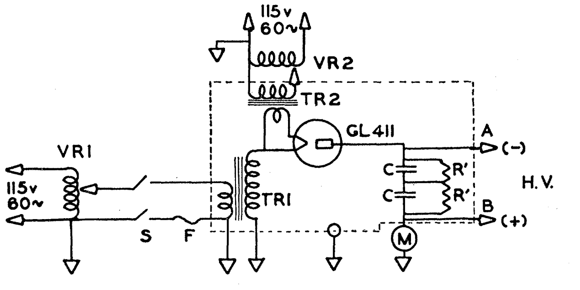

FIG. 1. Electronic power supply producing high voltage for electric field. VR_1, Powerstat operating from constant voltage transformer; S, double-pole single-throw switch; F, 6-amp fuse; TR_1, high-voltage transformer, 100-kv maximum; TR_2, filament transformer, insulated for 150 kv; VR_2, Variac input to filament transformer; $GL411$, high vacuum rectifier, capable of rectifying 150 kv; C, 0.025-μf, 40-kv dc capacitor; R', five 10-megohm resistors in series; M, 0–1 dc milliammeter in series with R' to measure high-voltage output; A, B, high-voltage terminals. A is connected to plate of experimental tube, B is connected to grounded end of tungsten filament. Components contained in dashed rectangle were immersed in oil in steel drums, providing electrostatic shielding and diminishing corona discharge. The output of the power supply was continuously variable from 0 to 72 kv.

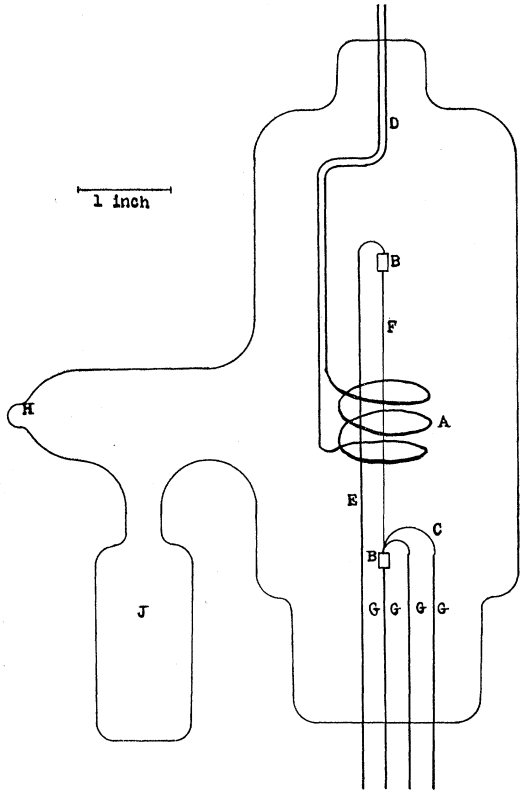

FIG. 2. Experimental tubes No. 2 and No. 3. A, spiral "plate," 3 turns of 0.030-in. tungsten rod, 2.54-cm diameter, 1.90-cm length; B, nickel chucks supporting filament and thermocouple hot junction; C, iron-constantan thermocouple—the iron and constantan wires were spotwelded to 0.050-in. nickel wires G (diameter of thermocouple wires was 0.001-in., hot junction was spotwelded to 0.004-in. diameter nickel wire which was inserted into chuck B and held in contact with filament by a set-screw); D, plate support leads, 0.080-in. diameter nickel rods spotwelded to the tungsten spiral and press leads; E, 0.030-in. diameter tungsten rod, sealed in 4-wire press and sealed in glass over its entire length except for hook at top; F, tungsten filament, 0.00045-in. diameter, 3-in. long, mounted along axis of spiral and 0.25 in. from support rod E; G, 0.050-in. diameter nickel-to-tungsten leads sealed in 4-wire press and supporting the tube elements; H, Seal-off; J, $VG1A$ ion gauge. Glass envelope and presses were Pyrex. Lower press was skirted (not shown). One end of filament F was connected to ground and terminal B' of Fig. 3 and B of Fig. 1, the other end was connected to terminal A' of Fig. 3 through support rod E.

The second and third tubes were identical but different from the first tube. The "plate" (A, Fig. 2) was a three-turn spiral of tungsten wire (diameter, 0.03-in.) which was spotwelded to the 0.08-in. diameter nickel press leads (D, Fig. 2). An alternating current of 25 amperes through the spiral heated it to 2400°K. (The spiral "plate" structure was chosen to simplify the outgassing procedure and to eliminate local heating of the glass walls of the tube experienced with the first tube.) The filament (F, Fig. 2) was a 0.00045-in. diameter tungsten wire. One end of the wire was supported by a tungsten rod, 3 in. long and sealed into a glass tube (E, Fig. 2). This glass covering minimized the escape of adsorbed gases from the support rod into the experimental tube after seal-off. (Since the thick rod was connected to the fine-wire filament, it could not be outgassed without burning out the filament.) Both tubes were evacuated to a pressure of 10^{-8} mm Hg. While outgassing tube No. 2, the thermocouple burned out, and after six days a gassy lead had raised the pressure to a value too high to permit high-voltage runs.

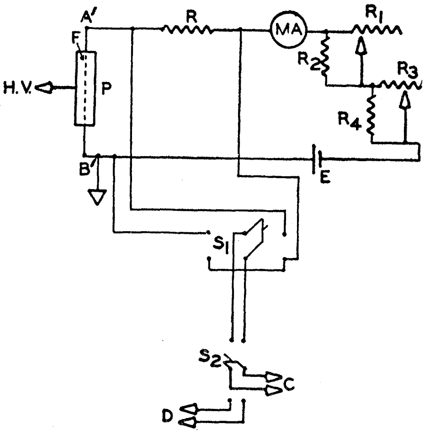

FIG. 3. Filament resistance and temperature measuring circuit. A', B', connected to ends of filament of experimental tubes (F, Fig. 2); R, standardized resistor, 9.9951±0.0003 ohms; MA, 0–10 dc milliammeter for approximate setting of current; R_1, 20K-ohm micropot variable resistor for fine adjustment of current; R_2, 200-ohm resistor; R_3, 250-ohm resistor, variable for coarse adjustment of current; R_4, 750-ohm resistor; E, new 2-volt lead-plate cell supplying current for measuring circuit; C, to Leeds and Northrup student-type potentiometer; D, to thermocouple of experimental tube; S_1, double-pole double-throw switch for connecting potentiometer across R, and R and F (filament) in series; S_2, double-pole double-throw switch for connecting potentiometer to either thermocouple or measuring circuit; P, plate of experimental tube; F, filament of experimental tube; H.V., to terminal A, Fig. 1.

The third tube survived the outgassing procedure and was used for most of the experiments.

The ion gauges used for pressure measurement also served to clean-up the tubes after seal-off by electrical pumping action.[7] The ultimate vacuum attained in each tube was 10^{-8} mm Hg or lower. The outgassing procedure for all tubes included the following steps:

(1) The presses, chucks, springs, and plates were placed in an auxiliary vacuum system and outgassed by induction-heating at temperatures of 1800°K to 2000°K for one hour.

(2) After assembling the experimental tubes, they were evacuated to a pressure of 10^{-6} mm Hg. The spiral "plate" (A, Fig. 2) of tubes No. 2 and No. 3 was heated to 2400°K by an alternating current of 25 amp for 1 hour. The filaments (F, Fig. 2) were outgassed by flashing several times to 2700°K by using alternating current to eliminate "dc etch" and insure a smoother surface. Throughout the outgassing of the tube elements, a refrigerated trap (acetone and solid carbon dioxide) was used.

(3) The entire experimental tube was baked at 500°C for 5 hours while the pressure was maintained at 10^{-6} mm Hg or lower.

(4) Steps (2) and (3) were repeated.

(5) The refrigerant was changed to liquid air. The plates and filaments were again outgassed [step (2)] until the ion gauge registered no change in pressure when the elements were flashed.

(6) The tubes were sealed off while the elements were hot. The ion gauge was operated continuously, and used for "electrical pumping"[7] after seal-off.

This procedure consistently resulted in an ultimate pressure of 10^{-8} mm Hg or lower. As a result of the outgassing, a visible layer of metal was deposited on the walls of the tubes except where the skirted presses by shadowing prevented the deposition of a continuous conducting layer between filament and plate.

The measuring circuit (Fig. 3) consisted of a standardized resistor, a Leeds and Northrup student-type potentiometer, and a constant current source. The standardized resistor (R, Fig. 3) and the experimental filament F were connected in series with the constant current source and the potentiometer was used to measure the potential drop across R and that across R and F in series. The filament resistance R_F was calculated by

$$R_F = R(V_{R+F} - V_R)/V_R, \qquad (1)$$

where V_{R+F} is the potential drop across the resistor R and the filament F in series and V_R is the potential drop across R alone. The standardized resistor R was calibrated with a precision-type Wheatstone bridge as 9.9951±0.0003 ohms. The resistor was mounted in a copper cup filled with transformer oil in turn immersed in a constant temperature bath at 0°C. The constant current source (R_1, R_2, R_3, R_4 and the lead plate cell E, Fig. 3) was adjusted for currents of the order of 3 ma, the exact value being set such as to simplify the calculations. The magnitudes of the currents were small enough so that no measurable heating of the filament took place. The potential drops were measured with the potentiometer to 1 part in 100 000; hence the resistance of the filament was known with the same accuracy as the resistance of the standardized resistor R, about 3 parts in 100 000 or 0.003 percent. The potentiometer also was used to measure the thermocouple emf. The temperature of the filament was determined from standard conversion tables[8] to 0.01°C. The

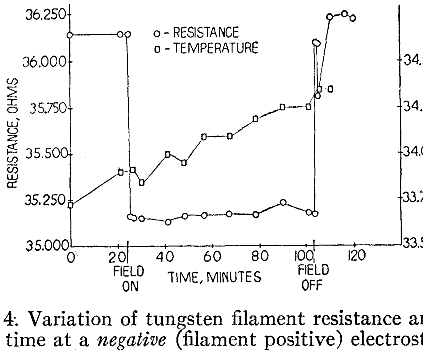

FIG. 4. Variation of tungsten filament resistance and temperature *vs* time at a *negative* (filament positive) electrostatic field of 4.54×10^6 volts/cm; tube No. 3; filament diameter, 0.00045 in.; initial no-field resistance, 36.140±0.003 ohms; initial no-field temperature, 33.90±0.01°C; pressure, 10^{-8} mm Hg.

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[7] D. Alpert, J. Appl. Phys. 24, 860 (1953).

[8] *Standard Conversion Tables* (Std. 21031) (Leeds and Northrup Company, Philadelphia).

TABLE I. Variation of filament resistance and temperature with time for a given applied negative field. Tube No. 3, filament diameter, 0.00045 inch; summary of Fig. 4-type runs.

Run No.	Applied field megavolts/cm	Abrupt change in filament resistance upon application and removal of field, ohms		Filament temperature change during time field was on,[a] °C	Calculated filament resistance change corresponding to observed temperature change,[a,b] ohms	Observed filament resistance change during time field was on,[a] ohms
		Decrease	Increase			
1	0.114	0.220	0.250	−0.02	−0.032	−0.095
2	0.227	0.100	0.150	+0.30	+0.050	+0.520[c]
3	0.454	0.420	0.174	−0.17[d]	−0.280	+0.420[c]
4	1.36[e]	0.500	0.500	+0.56	+0.088	+0.100
5	1.36[e]	0.480	0.650	+0.42	+0.070	+0.160
6	2.27	0.440	0.572	−0.55	−0.081	−0.230
7	2.72	0.900	0.773	−0.48	−0.078	−0.025
8	4.54[e]	0.995	0.937	+0.35	+0.057	+0.050
9	4.54[e]	1.110	1.050	+0.25	+0.039	+0.020
10	5.68	1.230	1.165	+0.17	+0.028	+0.010
11	7.26	1.160	1.300	+0.46	+0.075	+0.040

[a] A plus (+) sign denotes an increase; a minus (−) sign denotes a decrease.
[b] These resistance changes were calculated from the temperature coefficient of resistance of tungsten.
[c] The final resistances are considerably greater than the initial resistances, something not ordinarily observed.
[d] This is the only case of a resistance increase accompanied by a temperature decrease.
[e] These measurements were made to investigate the possibility of an electrostatic capacitance effect as the cause of the resistance decrease upon application of the field. For the first pair of values, the ground connection was reversed before the second measurement; i.e., the filament was inverted relative to the connections A and B and A' and B' (Figs. 1 and 3). The same was done between the second pair of measurements at a field of 4.54×10^6 volts/cm. In both cases, the resistance decreased upon application of the field and increased upon its removal. It was concluded therefore, that the resistance change is not due to an electrostatic effect involving the polarity of the filament.

following procedure was used in making each run involving measurement of the resistance of the filament:

(1) Ice and water were placed in the constant temperature bath of the standardized resistor. About one hour was allowed for attainment of thermal equilibrium. The constant current source was turned on and adjusted to a chosen value.

(2) The pressure in the experimental tube was measured and the ion gauge turned off and all elements grounded. A few minutes were allowed for the tube to cool to room temperature following the heating caused by the ion gauge.

(3) The potentiometer was calibrated against a new calibrated standard cell.

(4) The potential drops appearing across the resistor R and across R and the filament F in series were measured.

In some cases, the filaments were flashed (as described in the outgassing procedure) just before the filament resistance was measured. This was done to clean the filament of adsorbed gases. The filament resistance was measured as soon as the filament cooled to room temperature (requiring about 3 to 5 minutes). No difference in resistance was observed when the filaments were flashed or not prior to measurement. At the operating pressures employed, the gases evaporated during the flashing were very likely re-adsorbed while the filaments were cooling. Hence for most of the experiments, the filaments were not flashed.

RESULTS

The several experiments performed may be classified as follows:

1. The resistances of the filaments were measured as functions of time for given negative and positive electrostatic fields. A *positive* field is one with the plate electrically positive relative to the filament; a *negative* field is one with the plate negative relative to the filament.

2. The resistances of the filaments were measured *vs* increasing and decreasing negative and positive electrostatic fields.

3. The temperatures of the filaments were measured *vs* time for given negative and positive fields; and *vs* increasing and decreasing electrostatic fields.

4. The filament-to-ground electric current was measured as a function of the fields before and after the filament were vaporized. This was done in order to determine the relative magnitudes of the ion current, photocurrent, and the leakage current along the glass envelope of the experimental tubes.

Most curves for the experimental data are drawn with straight lines connecting plotted points. Smooth curves are drawn where a continuous variation is suggested or suspected.

A typical curve from the first and third groups of experiments (resistance and temperature *vs* time for given negative field) is shown in Fig. 4. The principal results obtained in this series of experiments are tabulated in Table I. Figure 5 is a typical curve of the same kind of experiment for a positive field. Table II lists the principal results of this set of experiments. The positive fields were necessarily weaker than the negative fields because of the possibility of field emission of electrons by the filament. Field strengths were calculated from assumed ideal cylindrical geometry.

It is observed for the experiments summarized in Tables I and II that in *every case* the resistance of the filament decreased abruptly upon application of the electric field and increased abruptly upon its removal,

Table II. Variation of filament resistance and temperature with time for a given applied positive field. Tube No. 3, filament diameter, 0.00045 inch; summary of Fig. 5-type runs. (The values for the weak fields show a smaller abrupt resistance change than for corresponding negative fields; whereas for the strong fields, the abrupt resistance change is larger than for corresponding negative fields.)

Run No.	Applied field megavolts/cm	Abrupt change in filament resistance upon application and removal of field, ohms		Filament temperature change during time field was on,[a] °C	Calculated filament resistance change corresponding to observed temperature change,[a,b] ohms	Observed filament resistance change during time field was on,[a] ohms
		Decrease	Increase			
1	0.454	0.088	0.062	+0.19	+0.032	+0.076
2	0.908	0.073	0.034	+0.16	+0.032	+0.035
3	1.14	0.605	0.265	+0.09	+0.016	+0.305
4	1.36	0.815	0.350	+0.30	+0.048	+0.420

[a] A plus (+) sign denotes an increase; a minus (−) sign denotes a decrease.
[b] These resistance changes were calculated from the temperature coefficient of resistance of tungsten.

regardless of the direction of the field. The abrupt decrease in resistance of the tungsten filament upon application of the field is contrary to Vissat's[3] results, but agrees with Worthing's.[1] In all, some fifty cases of this decrease were observed with tube No. 3 and some six cases with tube No. 2 before the filament was destroyed by arcing over in the latter case. All curves followed the same general pattern; upon application of the field the resistance of the filament abruptly decreased, while the field was held constant the resistance increased slightly; upon removal of the field the resistance of the filament increased abruptly to nearly its initial no-field value. The magnitudes of the abrupt resistance changes depend upon the field strength and vary from a few tenths to slightly more than one ohm; the slight change during the time the field was constant seemed to be independent of the field strength and was of the order of a few hundredths ohm.

In nearly every case, the temperature change of the filament is enough to account for a considerable part of (and sometimes nearly all) the resistance change during the time the field was on, but cannot account for the abrupt decrease or increase upon application or removal of the field.

Figures 5 and 6 were obtained at the same positive and negative field strengths of 1.36×10^6 volts/cm. They were taken in immediate succession. In both cases the resistance change upon application of the field was about 1.25 ohms. Except for the difference in time, the two curves may be almost superimposed. Again, the temperature change was sufficient to account for a considerable part of the resistance change while the field was on.

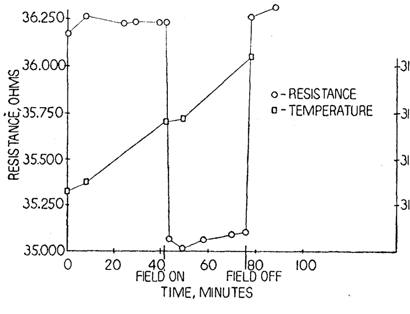

Fig. 5. Variation of tungsten filament resistance and temperature *vs* time at a *positive* (filament negative) electrostatic field of 1.36×10^6 volts/cm; tube No. 3; filament diameter, 0.00045 in.; initial no-field resistance, 36.240±0.003 ohms; initial no-field temperature, 31.28±0.01°C; pressure, 10^{-8} mm Hg. Calculated resistance change from observed temperature change, 0.022 ohm; observed resistance change, 0.085 ohm.

The initial abrupt resistance decrease upon application of the negative field *vs* the applied electric field is shown plotted in Fig. 7, the data being taken from Table I. The smooth curve shown, which fits the experimental curve quite well, is a parabola and its equation is

$$\Delta R = \alpha E^{\frac{1}{2}}, \tag{2}$$

where ΔR is the abrupt decrease in filament resistance upon application of the field, α is a constant of value 0.46 ohm cm$^{\frac{1}{2}}$ volts$^{-\frac{1}{2}}$ and E is the magnitude of the applied field in megavolts/cm.

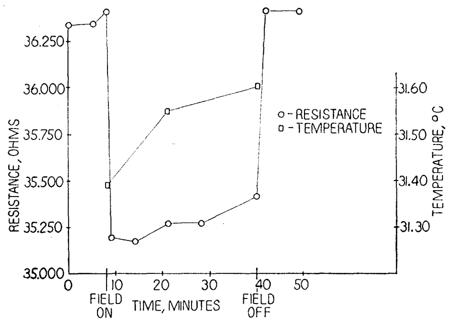

Fig. 6. Variation of tungsten filament resistance and temperature *vs* time at a *negative* field of 1.36×10^6 volts/cm (same magnitude as Fig. 5); tube No. 3; filament diameter, 0.00045 in.; initial no-field resistance, 36.352±0.003 ohms; initial no-field temperature, 31.39±0.01°C; pressure, 10^{-8} mm Hg. Figures 5 and 6, for the same magnitude of field strength, show that the temperature and resistance changes of the filament do not depend upon the direction of the applied field. Calculated resistance change from observed temperature change, 0.032 ohm; observed resistance change, 0.208 ohm.

Figure 8 shows the variation with applied electric field of the abrupt increase in filament resistance upon removal of the field. The smooth curve is a parabola satisfying Eq. (2) with $\alpha=0.46$ as in Fig. 7. It is clear that both the decrease and increase in filament resistance upon application and removal of the electric field vary with the field in the same way. Curves similar to Figs. 7 and 8 obtained from the data for the positive field curves are not very informative because all the points are clustered in the low-field region; however there appears to be no contradiction with Eq. (2).

The smaller long-time resistance changes cannot be correlated with field strength.

Figure 9 is a typical curve showing the variation of filament resistance *vs* negative applied electric field (class 2 experiments). This, and the other curves like it for both positive and negative fields also satisfy Eq. (2) with $\alpha=0.46$ as before, as is seen by Fig. 10. However, the agreement at larger strengths is not as good as for Figs. 7 and 8. No large temperature variation was observed for these resistance *vs* field experiments; any observed temperature changes were not nearly large enough to account for the resistance change.

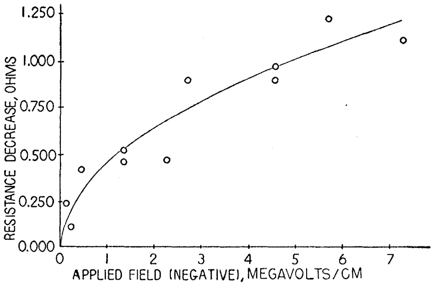

FIG. 7. Variation of the initial abrupt resistance decrease of the tungsten filament upon application of the negative field *vs* the magnitude of the applied electric field; tube No. 3; filament diameter, 0.00045 in. The smooth curve is a parabola satisfying the equation $\Delta R=\alpha E^{\frac{1}{2}}$, where $\alpha=0.46$ and E are the abscissa values. Data for this curve was taken from column 2, Table I.

The maximum no-electric field variation of filament temperature (measured over a period of about one hour) was 0.06°C. The variation of filament temperature during any given run (class 3 experiment) was of the order of 0.3°C to 0.8°C, approximately five or more times greater than the no-field variation. Thus the temperature change appears to be largely due to the electric field, and hence electron and/or ion bombardment of the filament resulting in a temperature rise is indicated. To explore the temperature effect more thoroughly, experiments were performed to determine the magnitude of the total direct electric currents passed by the experimental tubes. This was done by inserting a calibrated galvanometer in the ground connection to the filaments. The total direct current through the tube was assumed to consist of ion currents, photocurrents, leakage currents, and perhaps field-emission currents. Some subsequent incomplete experiments indicate that a significant percentage of the observed currents was photocurrent.

Figure 11 shows the variation of total current through a tube with negative applied electric field. The maximum current was 7.1×10^{-9} amp, at a field of 9×10^{6} volts/cm. A similar experiment with the same filament and a maximum positive field of 1.36×10^{6} volts/cm yielded a maximum current of 11.55×10^{-9} amp. Thus, if the positive fields could have been large enough, the total current would have been many hundreds of times greater than for the corresponding negative fields.

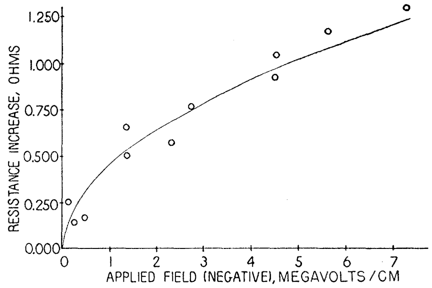

FIG. 8. Variation of the abrupt increase in resistance of the tungsten filament upon removal of the negative field *vs* the magnitude of the applied negative field; tube No. 3, filament diameter 0.00045 in. The smooth curve is a parabola satisfying the same equation as Fig. 7. Data for this curve was taken from column 3, Table I.

The final experiment performed on each tube was the measurement of the leakage current as a function of the applied field. The negative field only was used; for leakage current the same results should be observed for both positive and negative fields. The filaments were completely vaporized by connecting them across the output of a Variac and turning it on full after first heating the filaments to white heat at a low voltage. This worked effectively; no pieces of the filaments were observed remaining in the chucks. (It is noted that the tube pressure was not appreciably increased by vaporizing the filaments.) With the filament removed, it was assumed that the electric current through the tube upon application of the electric field was due primarily to leakage current with a small amount of ion current flowing between plate and filament chucks. A small amount of photocurrent also might be possible. The leakage current *vs* applied increasing and decreasing electric fields is shown by Fig. 12, and the fact that the curve shown is not a straight line indicates the presence of ion current along with the leakage current. A straight line determined by

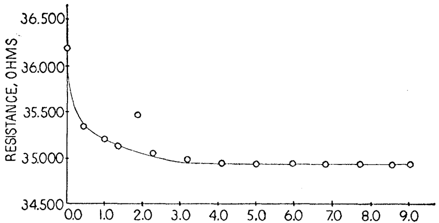

FIG. 9. Variation of tungsten filament resistance *vs* increasing applied negative electric field; tube No. 3. Curve is best smooth fit ignoring the point-well off the curve. Initial no-field resistance, 36.190±0.003 ohms; filament diameter, 0.00045 in.; pressure, 10^{-8} mm Hg.

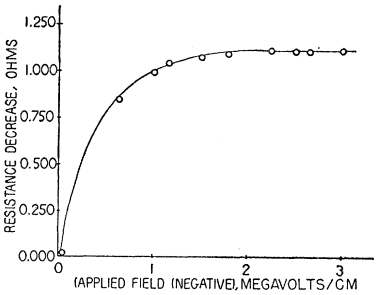

Fig. 10. Figure 9 data plotted as resistance change *vs* applied electric field, following Figs. 7 and 8. The smooth curve is the plot of Eq. (2) as before.

the small field points was drawn on the leakage current curve (dashed line, Fig. 12) to show the true leakage (Ohm's law variation) current.

The curve of Fig. 13, obtained by plotting the difference between the ordinates of Figs. 11 and 12 *vs* field, was considered to be the ion current (filament-to-plate alone) *vs* applied negative electric field.

The maximum ion current, 5.8×10^{-9} amp, in Fig. 13, yields 2.0×10^{12} (ions/sec) per cm^2 striking the filament. By kinetic theory, the number of molecules impinging per cm^2 of filament per second is 14.2×10^{12} at the measured pressure. Since the two values are about the same order of magnitude it may be concluded that there was enough gas present in the tube to produce the ion currents observed. Another simple calculation indicates that if any field emission current was present, it was so small as to be completely masked by the ion and photocurrents in the tube.

SUMMARY AND DISCUSSION

The experiments show in general that the resistance of a tungsten filament decreases abruptly upon application of a radial electrostatic field, increases slightly with time while the field remains constant, and increases abruptly when the field is removed. The magnitudes of the abrupt resistance changes are related to the magnitude of the field by Eq. (2). The resistance *vs* continuously varying electric field strength also follows Eq. (2).

Several experiments were performed in an attempt to detect some electrostatic capacitance effect which could account for the abrupt resistance changes, but none was found. Since no complete investigation of this type of effect was made, it is still possible that some obscure capacitance effect is present.

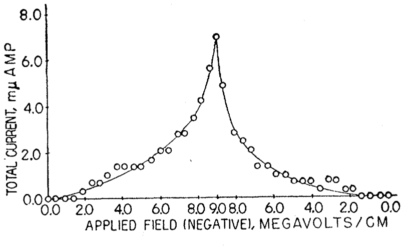

Fig. 11. Variation of total direct electric current (ion plus leakage) through tube *vs* increasing and decreasing negative applied electric field; tube No. 3; filament diameter, 0.00045 in.; pressure, 10^{-8} mm Hg; current was measured with a calibrated galvanometer in series with filament and ground.

The small resistance change with time during the application of a constant applied electric field was always accompanied by a temperature change. The observed temperature change accounted for a significant part of this resistance change, and since the temperature distribution of the filament was not known, it seems quite reasonable to assume that the entire small resistance change is associated with temperature. This temperature change would be due to the heating of the filament by current-carrier bombardment.

No specific attempt was made to determine the effect of pressure on the change in resistance.

It was generally observed that the final resistance (after the field was removed) was approximately equal to the initial no-field resistance, although not exactly so as reported by Worthing and Estabrook.

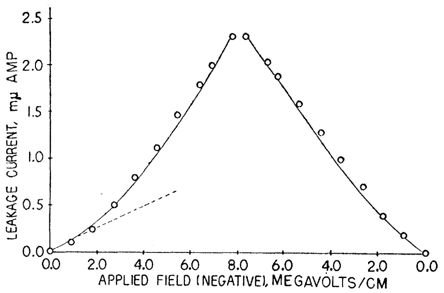

Fig. 12. Variation of leakage current *vs* increasing and decreasing negative field; tube No. 3. Dotted line indicates an Ohm's-law variation. Maximum current, $(2.3\pm0.1)\times10^{-9}$ amp; filament diameter, 0.00045 in.; pressure, 10^{-8} mm Hg; current was measured with a calibrated galvanometer in series with filament and ground.

It is interesting to compare the present results with those of Worthing,[1] Estabrook[2] and Vissat.[3] Worthing observed an abrupt *decrease* in the resistance of a heated tungsten filament upon application of a negative field and an increase upon removal of the field. This is in agreement with the results of the present investigation. Estabrook observed an abrupt *increase* in the resistance of a heated molybdenum filament upon application of the field and an abrupt decrease upon its removal. He assumed that this result was due to the use of molybdenum instead of tungsten. Vissat, with tungsten at temperatures up to 580°C, observed an abrupt *increase* in resistance upon application of the field and an abrupt decrease upon its removal. This agrees with Estabrook (assuming tungsten and molybdenum behave similarly) but not with Worthing or the present results.[9]

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[9] During some of the preliminary experiments of the present investigation increases in tungsten resistance with applied electric field were observed—in apparent agreement with Vissat. However,

Again, it should be emphasized that in the present investigation much better vacuum techniques were available, making possible higher vacua (10^{-8} mm Hg or lower as compared with 10^{-5} to 10^{-7} mm Hg for Worthing, Estabrook, and Vissat). More vigorous outgassing of the experimental tubes was employed in the present work and the tubes were sealed off, whereas Estabrook and Vissat employed waxed glass-metal seals and continuously pumped their tubes. Reid[6] states that no resistance change should occur at lower pressures than those of Estabrook and Vissat—in contradiction to the present experimental findings.

None of the earlier investigators[1–8] considered positive fields; nor did they observe resistance changes below 0.5×10^6 volts/cm. The previous investigators did not include direct measurement of the filament temperature although Vissat[3] attributed the resistance change to heating of the filament. As noted above, the temperature effect is significant, accounting roughly for the time change of resistance with field on but not for the more unusual abrupt change upon application or removal of the field.

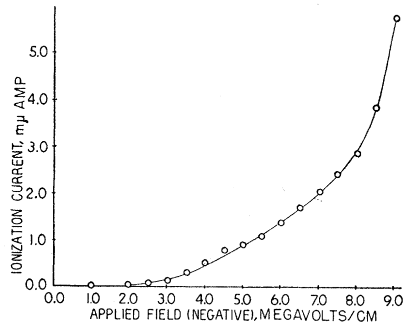

FIG. 13. Variation of ion current *vs* negative electric field; tube No. 3. Points obtained by subtracting ordinates of Fig. 11 from those of Fig. 10 and plotting *vs* field. Maximum current, $5.8\pm0.1\times10^{-9}$ amp; filament diameter, 0.00045 in.; pressure, 10^{-8} mm Hg.

Several theories have been developed for the resistance *vs* applied field effect but none has been found very successful. Greibach[5] attempted a theoretical explanation of Worthing's results based on classical thermodynamics of dipoles. He expressed the thermodynamic probability of evaporation of an atom from the surface of the filament in terms of the filament temperature and the applied electrostatic field. The uncharged evaporated atom becomes a dipole through the effect of the radial field which is more uniform and stronger at the end of the dipole nearest the filament resulting in attraction of the dipole for the filament. Thus the electrostatic field inhibits evaporation of the metal and the rate of evaporation (and consequently the rate of change of filament resistance) decreases. Analytically, integrating throughout the volume of the system, Greibach obtained an expression for the ratio of evaporation rate with field on to field off. His theoretical result for this ratio is but 1 percent approximately of Worthing's experimental value. Greibach attributes this discrepancy to his assumption of ideally clean, smooth surfaces whereas experimental filaments possess surface irregularities. (Since Worthing used dc heating of his filaments, they were subject also to dc etch production of patches.[4])

A different approach was employed by Reid[6] who designed an adsorption theory specifically for Estabrook's data.[2] He calculates, from a Maxwellian distribution of the velocities of the evaporated Mo atoms (including also some oxygen atoms which are carried off with the molybdenum), the ratio of evaporation rates of Mo with the electric field on to that with field off. The analytic theory requires the insertion of certain somewhat arbitrary parameters dependent on surface conditions of the Mo wires. Different wires require different values for these parameters, and there is no experimental procedure to enable an unique determination of these parameters. Hence, though plausible, the theory contains undesirable arbitrary procedures. Also, it should be noted that a suitable theory should explain the sudden resistance decrease upon application of the field and the increase upon removal of the field. Reid's theory attempted an explanation of the increase upon application of the field and decrease upon its removal.

It has not been possible so far to work out a theory explaining the present results. Reid's theory[6] does suggest that the abrupt resistance changes observed may depend on the gas content of the tungsten filament surface. A confident use of his theory will require a good deal more information on the exact nature of the tungsten filament surfaces, obtained perhaps by employing the Müller field-emission microscope technique.

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there were indications that large temperature changes (large compared to what was observed in the later more reliable experiments), caused perhaps by considerable ion bombardment in the higher-pressure vacua of the preliminary experiments, were present. Hence a true resistance increase *vs* applied field effect was not considered to be present.