

## Visual Observations on the Malter Effect<sup>1</sup>

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The thin film field emission (Malter effect) from  $\text{Al}_2\text{O}_3$  films on Al was investigated (1) by coating the film with a fine dust of willemite and observing the behavior of the primary beam; (2) by forming an electron image of the surface by means of the Malter current from it. The behavior of these films, while exhibiting the Malter effect, may be summarized as follows: 1. The potential of the front surface of the electrode is a saw-tooth function of time at any point, and nonuniform over the surface at any instant. 2. The current density of the primary beam at the surface varies, correspondingly, because of the varying electric field above the surface. 3. A time lag exists between the application of voltage across the film and the establishment of the Malter current. 4. The Malter current issues chiefly from a number of isolated points on the surface, and the current from any one of these points varies with time. 5. The emitting points are scattered over the entire surface of the electrode, with some preferential grouping in the region covered by the primary beam. 6. Some of the electrons constituting the Malter current have a kinetic energy corresponding in order of magnitude to the voltage drop across the film. 7. The Malter electrons leave the film with a wide range of speeds.

### INTRODUCTION

A NEW type of electron emitter, consisting of a thin film of insulating material on metal, has been studied by Malter. Such a film, when bombarded by electrons, emits current, many times larger than the primary current, to a collector which is held at a positive potential with respect to the metal underlying the film. Malter's explanation of the effect is that secondary emission from the surface of the film keeps it positive with respect to the metal backing. A high gradient is thus established through the film which results in the emission of electrons from the metal. Our observations agree with this explanation.

The object of these experiments was to test whether the thin film field emission from a film of  $\text{Al}_2\text{O}_3$  on Al is proportional to the primary current density. Two methods were used. First, the surface of the film was coated with a fine dust of synthetic willemite, so that the behavior of the primary beam could be followed. So far as we could tell, this trace of fluorescent powder had no effect on the emitting properties of the electrode. Later, an electron image of the surface was formed by means of the Malter current from it.

### WILLEMITE ON DISK; BEAM FOCUSED

Figure 1 shows a tube used for the first method. The Malter electrode  $A-M$  was cut from a sheet supplied us by the Aluminum Company of America. The film of electrolytic  $\text{Al}_2\text{O}_3$  was about  $10^{-3}$  cm thick, clear and glassy. After activation<sup>1</sup> with caesium and oxygen, magnesium getter was flashed and the tube was sealed off the pump.

With  $A-M$  floating, the primary beam formed a steady fluorescent spot on  $M$ . The beam was not noticeably bent after entering the collector cylinder  $C$ , and the spot did not noticeably move when  $A$  was connected to  $C$ . The floating potential of  $M$  therefore did not differ by more than a few volts from the potential of  $C$ .

The spot was focused to a diameter of about 1.5 mm,  $R$  was set at about  $1/2$  megohm, and  $A$  was made increasingly negative to  $C$ . At first the spot was stationary and no current flowed through the meter  $T$ . When a critical voltage near  $V=50$  v was reached, the meter suddenly deflected and the spot was thrown upward off the disk onto the wall of  $C$ , indicating that  $M$  had suddenly gone strongly negative to  $C$ . The spot then drifted down the side of  $C$  slowly (seconds), flickered about at the edge of the disk, and finally returned rather rapidly across  $M$  toward its former steady position. While the spot was drifting back across  $M$ , an increasing electron current of the order of  $100 \mu\text{A}$  flowed through

<sup>1</sup>L. Malter, Phys. Rev. 49, 478 (1936); 50, 48 (1936). Malter calls the phenomenon "thin film field emission." We use the shorter name here for reasons of convenience.

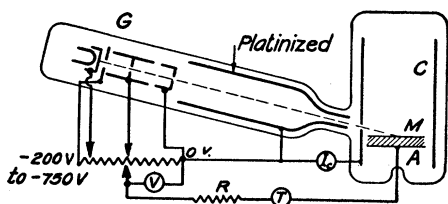


FIG. 1. Tube and circuit used in the first method of investigation. The surface  $M$  of the Malter film and the inside of the collecting cylinder  $C$  are dusted lightly with fluorescent powder.

the meter to  $A$ . Sooner or later there was another sudden deflection of the spot off the surface. The current through the meter dropped practically to zero at each such excursion. The frequency of the excursions increased with increasing  $V$  and with decreasing  $R$ .

It seems likely that after a discharge, when the primary beam is not striking  $M$ ,  $M$  returns toward the potential of  $C$  by collecting positive ions formed from residual gas in the space. When  $M$  has become positive enough so that the beam again strikes it, the return is accelerated by the addition of the excess secondary emission to this small positive ion current. The spot has difficulty at the edge of the disk, probably because the bare Al, highly negative, is exposed there.

When  $R$  was increased to 5 or 10 megohms, there was a range of voltages  $V$  over which the current through  $T$  was quite steady, and the primary spot moved about only slightly and erratically on  $M$  without leaving the disk.

#### WILLEMITE ON DISK; BEAM DEFocused

The spot was defocused to cover about  $1 \text{ cm}^2$  on the floating disk. When  $R$  was  $1/2$  megohm and  $V$  was sufficiently high, this broad spot was thrown off the disk just as the focused spot had been. With  $R$  5 to 10 megohms and  $V$  in the range for which the focused spot moved about only slightly on  $M$ , the broad spot showed a striking "Swiss cheese pattern" (Fig. 2). In the green fluorescent patch, dark regions roughly circular and a few mm in diameter appeared suddenly and immediately began to disappear by shrinking in uniformly from the edges. At any instant the green patch was mottled with these shrinking dark areas. There was no marked limiting action of the edge of the green region—

the edge was overlapped indifferently by dark holes centered out in a part of the disk which the primary beam had not been striking. The dark holes varied considerably in original size. Their maximum size and the frequency of their appearance increased with increasing  $V$  and with decreasing  $R$ . Deflection of the beam onto  $C$  was apparently a limiting case in which a single dark hole covered the entire disk.

These observations indicate that the entire surface  $M$  is "normally" at a fairly uniform potential positive to the Al beneath it. Now and then certain areas suddenly lose their positive charge. The circular shape of these areas suggests that a sudden spray of electrons is emitted from a point on  $M$ , the center of the circle, and discharges the surrounding region. The magnitude of such a spray, and hence the area discharged, is limited by the size of the ballast resistance  $R$ . The fact that the dark holes shrink inward gradually suggests that the potential of a discharged region decreases gradually toward the center. Positive ion current from the space and conduction over the surface presumably both aid in the recharging. From the time of recharging (about  $1/4$  sec. for completion), we can estimate the surface resistivity as, at the most,  $10^{10}$  ohms. It seems plausible that such circular patches are being discharged suddenly and recharged gradually when the spot is focused to a small diameter, and that the changing local fields above  $M$  account for the slight erratic motion of a focused spot.

#### TIME LAG IN THE MALTER EFFECT

If the lead to  $A$  was opened and suddenly closed, the primary spot, even when  $R$  was 5 or 10 megohms, was thrown clear of the disk, and returned to its quasi-equilibrium position in the manner described above. We inferred from this that there is a time lag in the establishment of the Malter current of a greater order of magnitude than the charging time of the  $A$ - $M$  condenser through  $R$ . When the circuit is closed the full voltage  $V$  is impressed across  $A$ - $M$  until the Malter current sets up a drop in  $R$ . In this interval,  $M$  is discharged to  $A$  by a breakdown process. By finding what additional capacity between  $A$  and  $C$  was just large enough to

prevent these excursions, we were able to estimate that the time lag for this film was of the order of  $10^{-3}$  sec.

#### WILLEMITE ON DISK; PERSISTENT EMISSION

The Malter emission was excited in the normal way, with the primary spot either focused or defocused, and with  $R$  and  $V$  in the range appropriate for the existence of the Swiss cheese pattern. The primary beam was then cut off, either by biasing the grid of the gun or by cooling the cathode. The electron current through  $M$  to  $C$  persisted practically unchanged for a time ranging from seconds to hours. While this persistent current flowed, tiny bright spots of green could be seen here and there on  $M$ , together with a general very faint uniform fluorescence. The spots were somewhat concentrated in the region on which the primary beam had played, but not markedly so. The life of a spot was of the order of seconds, and longer the larger  $R$ . New spots continually appeared. A variety of experiments supported the belief that these tiny brilliant spots mark points on  $M$  from which the Malter electrons issue. For example, when a horseshoe magnet was brought up to the tube so that  $H$  ( $\sim 200$  gauss max.) was roughly parallel to  $M$ , these electrons were bent back and struck  $M$ , exciting it to fluorescence. New brilliant spots were apt to appear on regions thus bombarded. When a brilliant spot appeared near the edge of the disk, where the negative bare metal was exposed, the electrons were bent back toward the disk by the electric field and excited fluorescence in a fan of lines radiating from the spot (Fig. 3). In previous work with these thick films we have found that the persistent Malter current usually is unchanged until it suddenly goes to zero. In this tube, the persistent current sometimes decreased stepwise with time, the average number of bright spots decreasing with each downward step. It was sometimes possible, after the current had fallen to, say,  $1/10$  its initial value, to build it up by deflecting the Malter electrons back onto  $M$  with a magnet, thus exciting new emitting spots. In no case was it possible to restore the current after it had fallen to zero, other than by again bombarding the surface.

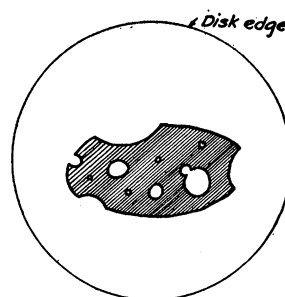


FIG. 2. Typical appearance of the surface when a fairly steady Malter current, limited by a high resistance, is flowing. The hatched region is being struck by the primary beam. The circular inclusions, which are shrinking in diameter, are areas recently discharged.

The fluorescence threshold for the willemite is about 50 v. It is evident that at least some of the electrons in the persistent Malter current leave  $M$  with kinetic energy corresponding at least in order of magnitude to the voltage drop between  $A$  and  $C$ . This is in agreement with a rough estimate of their momentum, based on the bending of their paths in the magnetic field. The positive potential of  $M$  probably is maintained partly by a small positive ion current from the space and partly by secondary emission caused by the outgoing persistent current.

#### SCINTILLATIONS

If  $R$  was low ( $< 10^5$  ohms), or if a capacity  $> 0.1 \mu F$  was put between  $A$  and  $C$ , when  $V$  was increased above a critical value, discharge of  $M$  occurred as a momentary bright spot or scintillation (entirely distinct from the persistent glowing green points described above). If such a scintillation occurred after the primary beam had been cut off, the persistent current immediately dropped to zero. These scintillations are apparently large-size occurrences of the same type as the dark holes in the Swiss cheese pattern.

#### OTHER FILMS STUDIED

We repeated these experiments on another electrode with a thick film ( $\sim 10^{-3}$  cm) and on an electrode with a much thinner film ( $\sim 3 \times 10^{-5}$  cm). With the thin film observation was harder, since the critical voltage for breakdown was lower, and hence the emerging electrons were less effective in exciting fluorescence. The re-

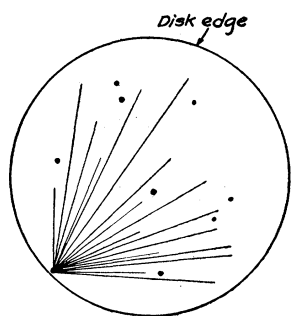


FIG. 3. Typical appearance of the surface when a persistent Malter current, limited by a high resistance, is flowing after the primary beam has been cut off.

sults with the thin film, however, were not inconsistent with those described above.

#### MALTER CATHODE IN AN IMAGE TUBE

The tube used for the second method of observation was similar to the image tube described by Zworykin and Morton<sup>2</sup> and about half as large (Fig. 4). Originally the cathode was a nickel disk with three strips of the thick-film aluminum riveted to its surface. These particular samples showed no Malter effect. However, it was possible to form a clear image of the cathode by the photoelectrons it emitted when the circular filament  $F$  was lighted.

We substituted for this cathode a thin-film electrode, 2 cm in diameter, surrounded by a coplanar Ni guard ring. This electrode showed a good Malter emission when we used either light from  $F$  or electrons from the gun to excite it, and connected the focusing rings together as a collector. Photoelectric emission from the surface is as effective as secondary emission in maintaining the surface at a positive potential.

With the usual image-tube potentials, and the film excited by light from  $F$ , the following cyclic behavior was observed:

At first there was a fairly sharp image of disk and guard ring, with a magnification of about 1. In the image, the disk was darker than the guard ring. The magnification began to increase, at first slowly then faster, and here and there a caustic-shaped splotch of fluorescence appeared on the screen for an instant. These splotches became more frequent and the magnification

increased at a faster rate, until a blurry image of the disk alone more than covered the entire screen. Then suddenly the image reverted to its original size and sharpness, and the transient splotches ceased. This cycle occurred regularly with a period of about two seconds. Its period was less the higher the temperature of  $F$ . A single bright scintillation occurred on the film when the image returned to its original condition. This scintillation did not cause a burst of fluorescence on the screen.

This behavior can be explained on the same basis as the previous observations. So long as photoelectric emission from the surface continues, the surface becomes more and more positive. When the surface has charged up sufficiently, Malter current begins to flow out through the film, and reaches the screen to form the bright transient splotches. The Malter current increases rapidly with increasing potential of the film surface. Finally, the voltage across the film is so great that a scintillation occurs and the entire surface returns to the potential of the Al backing. Then the cycle is repeated.

When electrons from the gun were used as the exciting agent, the same cyclic behavior was observed. The splotchy images of the points from which the Malter emission came were apparently scattered over the disk, and were not confined to the area struck by the beam.

On removing the primary excitation, the continuous background due to photoelectric emission or to normal secondary emission vanished, as did the expansion and contraction of the image.

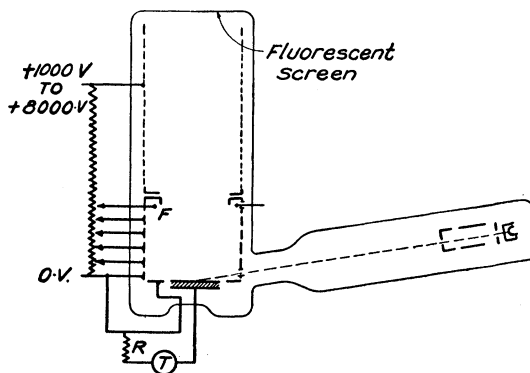


FIG. 4. Tube and circuit used for forming an electron image of Malter film on a fluorescent screen.

<sup>2</sup> V. K. Zworykin and G. A. Morton, *J. Opt. Soc. Am.* **26**, 181 (1936).

If there was no large resistance in series with the Malter electrode, the splotches corresponding to the Malter emission also disappeared. By putting 10 to 30 megohms in this circuit we could keep these splotches on the screen for a long time after stopping the primary excitation. They behaved in the same way as the fluorescent points which had marked the persistent Malter current through a film dusted with willemite.

The persistent splotches were irregular stars (Fig. 5), which could not be focused to point images of the emitting spots on the disk. We conclude that the Malter electrons have a wide range of speeds, for if their velocities differed only in direction it would be possible to bring them to a point focus.

There was no difference in appearance between the persistent splotches and the transient ones that appeared during excitation. The splotches are to be identified with the fluorescent points on a film emitting after the exciting agent has been shut off. The cyclic behavior of the image during excitation is to be associated with the sudden excursions of the primary beam mentioned above, with the sudden appearance and gradual shrinkage of the holes in the Swiss cheese pattern, and with the scintillations. It appears that the Malter emission, and the bursts that discharge the surface either wholly or in part,

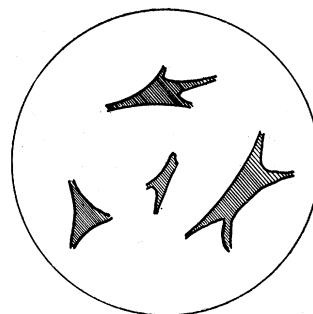


FIG. 5. Electron image of persistent Malter emission.

are two distinct types of conduction through the film.

#### APPEARANCE OF THE FILMS

We examined several thick-film samples under a microscope (magnification 300), both before and after use as Malter emitters. The only visible surface irregularities were long narrow slanting cracks through the oxide, particularly near the edge of the disk, which had been cut out with shears. When the electrode was in use, there was no tendency for concentration of the emitting points along these cracks. Under the microscope, points where large scintillations had occurred appeared as craters. The existence of the Malter effect did not depend on whether scintillation breakdown had previously taken place.