IEEE Transactions on Nuclear Science, Vol. NS-27, No. 6, December 1980

DIELECTRIC SURFACE DISCHARGES: DEPENDENCE ON INCIDENT ELECTRON FLUX*

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Abstract

A very extensive experimental study of planar-dielectric discharge dependence on monoenergetic 20 keV incident electron flux is reported. The discharge pulse characteristics studied are peak current, released charge, pulse duration and energy dissipated, all measured at load resistors attached to the dielectric specimen metal backplate and metal mask. The dependence of these characteristics on incident electron flux is described for Kapton H, Mylar and FEP Teflon, and only Kapton exhibits discharge characteristics which are significantly flux-dependent. It has also been found that Kapton and Teflon exhibit discharge fatigue, often producing a cessation of discharging after the occurrence of a few discharge arcs.

Introduction

It has been reported[1] that the properties of Kapton surface discharge arcs are dependent on the incident electron flux, in particular that the released charge can be roughly linearly proportional to the incident electron current density and that the peak discharge current also increases with increasing incident-beam current density. In the same paper it was also noted that a second-surface mirror array and a fiberglass specimen did not exhibit the same behavior. This incident flux dependence is very important in estimating the probable strength of discharges on spacecraft in synchronous orbit. It is also crucial in determining the relevance to spacecraft considerations of laboratory experiments carried out at the relatively high incident electron beam current densities which are useful for accelerated testing[2].

In the flux-dependence experiments referred to above[1], realistic large-area dielectric specimens were used, but the number of values of incident current densities employed was too small to get an accurate measure of the scaling laws which are applicable. Furthermore, existing information does not indicate whether or not other polymers used in space behave in the same way as Kapton. The experiments to be described in this paper were designed to provide the information referred to above, and also to provide additional data on the division of discharge current between the metal substrate and the metal mask used to define the exposed area.

The Experiment

The experimental arrangement is depicted in Fig. 1. The materials used were Kapton H with a vacuum-deposited aluminum backing, and Mylar and FFP Teflon without metallization, the three materials having thicknesses of 50 μm, 75 μm and 50 μm respectively. The incident beam energy was fixed at 20 keV and the beam uniformity over the exposed area was better than ±20% as measured by an array of five Faraday cups before and after the experiments; also, continuous monitoring with a single Faraday cup was provided during the experiments, The range of incident current densities used was 0.5 to 100 nA/cm^2. The exposed dielectric area was 11.7 cm^2 as defined by a circular aperture in a 1.6 mm thick aluminum mask, the aperture having a 45° bevelled edge to reduce emitted electron interception. The outer dimensions of the mask and substrate were 8 x 9 cm, making the exposed dielectric area appreciably smaller than the exposed mask area, in contrast to previous experiments[1] involving a very narrow edge clamp (equivalent to the mask). The measurement system employed a two-channel 400 MHz bandwidth oscilloscope connected through appropriate attenuators to the specimen substrate and mask, each shunted to ground with a 2.5 ohm load resistor made up of 8 low-inductance 20 ohm half-watt resistors in parallel.

Results for Kapton H

The substrate discharge current pulse is characterized by its peak current, released charge and duration, the latter two defined as

$$Q_s = \int I_s(t)\, dt \quad (1)$$

$$T_s = \frac{1}{I_s} \int I_s(t)\, dt = \frac{Q_s}{I_s} \quad (2)$$

in which I_s is the peak current. The energy dissipated in the substrate load resistor R is

$$E_s = R \int I_s^2\, (t)\, dt \quad (3)$$

Exactly the same formulas are used to characterize the mask current pulse, namely I_m, Q_m, T_m and E_m.

Figure 2 shows that I_s and Q_s exhibit a definite tendency to decrease with decreasing incident current density. This tendency is appreciably more gradual than one might expect from the previous results[1]. Futhermore, if one were to select only the strongest pulses observed in the range 1-10 nA/cm^2 (the tops of the vertical bars indicating measurement ranges), one would conclude that there is no significant incident-flux dependence at all. However, the points representing average values and the best-fit straight line probably provide better guidance for estimating overall trends.

Also shown in Fig. 2 is the pulse duration T_s which is very nearly constant, the indicated slope being small in relation to the indicated measurement ranges. This result is consistent with the notion that the pulse duration is determined by the specimen dimensions, because the discharge propagates at a well-defined velocity. This velocity can be estimated by dividing the aperture radius by the pulse duration, which gives 2.6x10^5 m/s.

Similar results for the mask current pulse are given in Fig. 3. The mask current pulse duration gives a discharge propagation velocity of 3.2x10^5 m/s. The energy dissipated in the load resistors attached to both substrate and mask are shown in Fig. 4 which indicates a very significant variation over the range of incident current densities.

As a check, these results for Kapton can be compared with previous results[2] for which the mask was connected directly to the substrate, causing the mask current to bypass the substrate load resistor. In the previous measurements at 80 nA/cm^2 and 11.7 cm^2, the

*Work supported by the U.S. Air force Weapons Laboratory and by NASA, through Grant NSG-7647.

0018-9499/80/1200-1770$00.75

straight-line-interpolated peak current was 20A. In the present measurements, the corresponding current would be the substrate current of 40A minus the mask current of 23A giving 17A, so the comparison in this case is very close.

Results for Mylar and FEP Teflon

Figures 5 and 6 display the substrate and mask pulse characteristics I, Q, T and E for both Mylar and Teflon. Not one of these characteristics displays any significant variation with incident-beam current density.

Mask-to-Substrate Ratios

Figures 7, 8 and 9 provide details of the mask-to-substrate ratios for the four averaged pulse characteristics and the three materials. There appears to be no significant flux scaling, although it is interesting to note that all the straight-line approximations for Teflon have negative slopes, while all those for Mylar and Kapton have positive slopes.

To interpret the mask-to-substrate ratios, let us postulate that the discharges are initiated very close to the mask edge where charge concentrations and fields are highest. The surface arcs then propagate inward and die out in the central region of the specimen, a further postulate which is consistent with the appearance of the arcs although their evolution in time has not been measured. As the arc propagates inward, it is reasonable to expect that more of its ejected electrons go to the chamber wall and fewer to the mask. Therefore the mask current pulse should decay more rapidly than the substrate current pulse. In effect this would shorten the mask pulse, as observed.

It is noted that the mask-to-substrate ratios are ordered $I_m/I_s > Q_m/Q_s > E_m/E_s$. To interpret this ordering, suppose that a current pulse consists of an instantaneous rise followed by an exponential decay. That is, take the currents to be zero for $t\leq 0$, and the for $t\geq 0$ take $I_s(t) = e^{-at}$ and $I_m(t) = ke^{-abt}$. The factor k allows for the smaller mask peak current and the factor b allows for the more rapid mask current decay. Equations (1), (2) and (3) then permit derivation of $I_m/I_s = k$, $Q_m/Q_s = k/b$, $E_m/E_s = k^2/b$, and $T_m/T_s = 1/b$. For the given conditions $k<1$, and $b>1$, it is clear that $k>k/b>k^2/b$, or in other words $I_m/I_s > Q_m/Q_s > E_m/E_s$ as observed.

The above formulas also suggest that the charge and energy ratios may be deduced from the peak current and duration ratios. This may be tested readily by using the average measured values from Fig. 7, 8 and 9, as indicated in the following table:

Material	I_m/I_s measured	T_m/T_s measured	Q_m/Q_s meas.(calc.)	E_m/E_s meas.(calc.)
Kapton H	.575	.77	.43(.443)	.26(.255)
Mylar	.65	.67	.43(.436)	.30(.283)
FEP Teflon	.69	.74	.51(.511)	.36(.352)

It should also be noted that by definition $T_s = Q_s/I_s$ and $T_m = Q_m/I_m$, so that $Q_m/Q_s = (T_m/T_s)(I_m/I_s)$ which is always less than I_m/I_s as long as $T_m < T_s$, for any pulse model.

In a foregoing paragraph it was postulated that the apparent shortening of the mask pulse might be due to electrons from the central region of the specimen never reaching the mask. The size of this central region can be estimated by starting with the notion that the propagation velocity v_p must be given by $v_p = r_s/T_s = r_m/T_m$ where r_s is the aperture radius and r_m is the arc length over which emitted electrons can reach the mask. This gives $r_m = r_s(T_m/T_s)$. If r_c is the radius of the central region referred to above, then $r_s = r_c + r_m$, from which $r_c/r_s = 1 - (T_m/T_s)$. Data from the above table gives r_c/r_s approximately in the range of 1/4 to 1/3. Therefore it would appear that there exists a central region of significant size, from which emitted electrons do not reach the mask.

Waiting-Time Between Discharges

As the incident current density is decreased, one would expect to wait longer for each discharge to occur, and this is what one finds in the course of performing discharge experiments[3]. For 75μm thick Mylar, typical waiting-times were 60, 15 and 2.5 minutes for current densities of 0.5, 5 and 50 nA/cm^2. For 50 μm thick Kapton there was less recorded data to work with, but the recorded waiting-times varied from 30 to 2.5 minutes for current densities from 0.5 to 50 nA/cm^2. For 50 μm thick Teflon, still fewer records were available, but existing data suggest waiting-times approximately equal to those for Mylar.

Specimen Fatigue

A single 75 μm thick Mylar specimen was used for a total of 66 discharges without showing any signs of fatigue such as changes in discharge strength or waiting time. The 50 μm thick specimens of Kapton and Teflon exhibited much more erratic behavior, however, with several specimens failing to discharge at all at low current densities. Considering only those specimens which did produce discharges, for Kapton the 49 discharges required 11 specimens and for Teflon the 38 discharges required 10 specimens.

This need for frequent specimen changes came about because of specimen fatigue. On 80% of the Kapton and Teflon specimens this fatigue took the form of cessation in discharge activity after 4 or 5 discharges. On the remaining 20%, "pinholes" or "punchthroughs" developed in the specimen, followed by very rapid but weak discharges of relatively long duration.

On an Incident Current Density Threshold for Discharge Occurrence

Consider a uniform charged particle beam of current density J, constant particle density N, particle charge e and velocity v, so that J = Nev, and suppose that this beam reaches the specimen after penetrating the potential barrier due to embedded charge. Suppose also that J_o and v_o are the values in the beam at some distance from the specimen, or in other words J_o would be the current density measured by a Faraday cup inserted in place of the specimen. Now if V_b and V_s are the beam accelerating voltage and the specimen surface potential, we have $eV_b = m v_o^2/2$ and $e(V_b - V_s) = m v^2/2$.

Thus
$$Ne = \frac{J_o}{v_o} = J_o\sqrt{\frac{m}{2eV_b}}$$

and
$$J = Nev = J_o\sqrt{\frac{m}{2eV_b}}\sqrt{\frac{2e(V_b-V_s)}{m}}$$

giving
$$J = J_o\sqrt{1-(V_s/V_b)}$$

Now the internal resistance of a specimen of thickness h, area A and resistivity ρ is R = ρh/A and the surface potential is

$$V_s = RJA = \rho\, h\, J_o\sqrt{1-(V_s/V_b)} \qquad (4)$$

Defining V_o to be the voltage drop across the specimen if it passed the total measured current density J_o, we have $V_o = \rho h J_o$.

Squaring equation (4) gives

$$(V_s/V_o)^2 + (V_s/V_b) = 1 \qquad (5)$$

Now consider as an example V_b = 20 kV, together with V_s = 13 kV and $\rho = 10^{13}\Omega$m suggested in the literature[1] as being appropriate for 50 μm thick Kapton on the point of punchthrough breakdown. Equation (5) gives J_o = 4.4 nA/cm^2 as being a threshold value below which the surface potential could not reach the breakdown level. As might be expected, this is somewhat higher than the value of 2.6 nA/cm^2 calculated previously[1] by ignoring the repulsive effect of accumulated surface charge. However, experimental results already described in this paper indicate the occurrence of discharges at 0.5 nA/cm^2. One possible interpretation is that at the point of discharge initiation the incident beam has been focussed to a current density several times its measured value, and indeed some evidence exists for increased charge concentration near a specimen edge[4]. However, equation (5) is directly relevant only to punchthrough breakdown, and the observed specimen damage patterns indicate that the majority of discharges initiate at the mask edge but do not involve punchthrough. Therefore equation (5) could at best apply only to a minority of discharge arcs on masked specimens, the rest probably initiating at points of locally high near-surface fields at the mask edge.

Conclusions

Among the three dielectric materials tested, Kapton is the only one exhibiting discharge pulse characteristics which are significantly dependent on the incident electron current density. For Kapton, previous work[2] had been carried out with an incident current density of 80 nA/cm^2, a value which just happens to give Kapton discharge pulse characteristics almost identical to those for Mylar and Teflon. It may be concluded that previous area-scaling results[2] are valid over a wide range of current densities for Mylar and Teflon, and in the case of Kapton they can be corrected for current density dependence by using the results presented here. Thus accelerated discharge testing at high incident current densities appears to be feasible.

Indirect evidence is presented indicating that electrons from the central region of the specimen may never reach the mask. Estimation of an incident beam current density threshold for discharge occurrence suggests that incident-beam focussing could be involved in punchthrough discharge occurrence at current densities below 4 or 5 nA/cm^2. Specimen fatigue has been noted, in the form of frequent, long, low-level discharge pulses signaling the occurrence of a dielectric specimen punchthrough.

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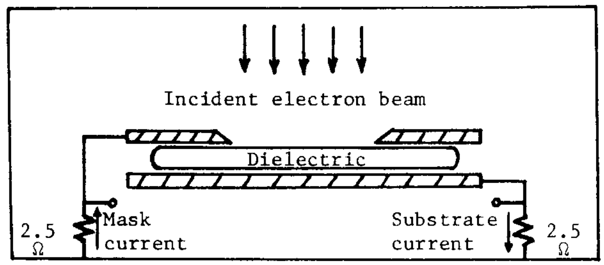

Fig. 1

Experimental arrangement in vacuum chamber

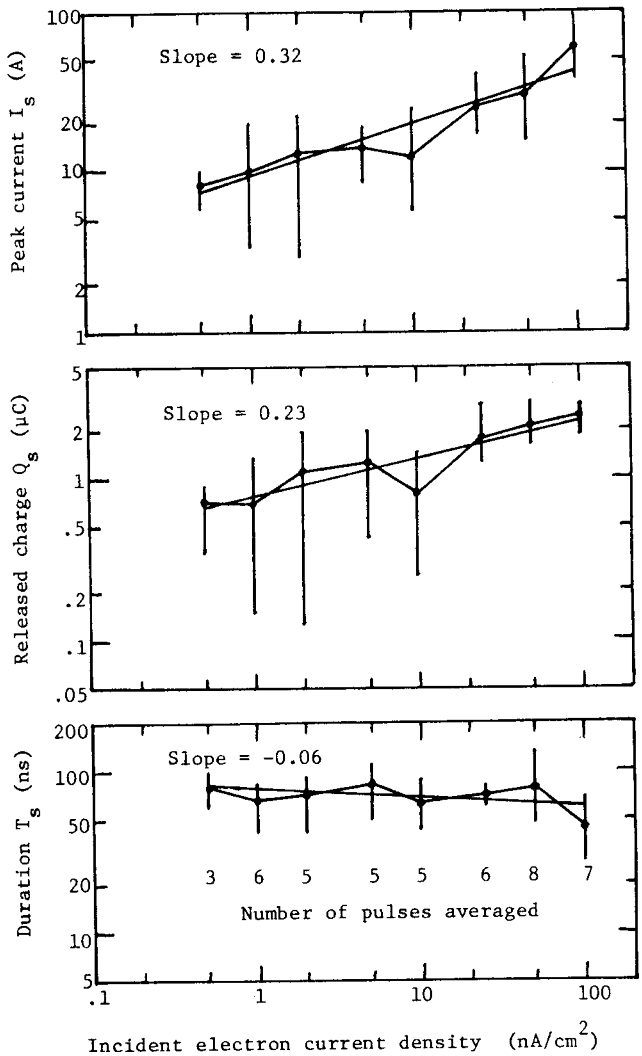

Fig. 2 Substrate discharge current pulse properties for Kapton H. Beam energy = 20 keV, specimen area = 11.7 cm^2, specimen thickness = 50 μm.

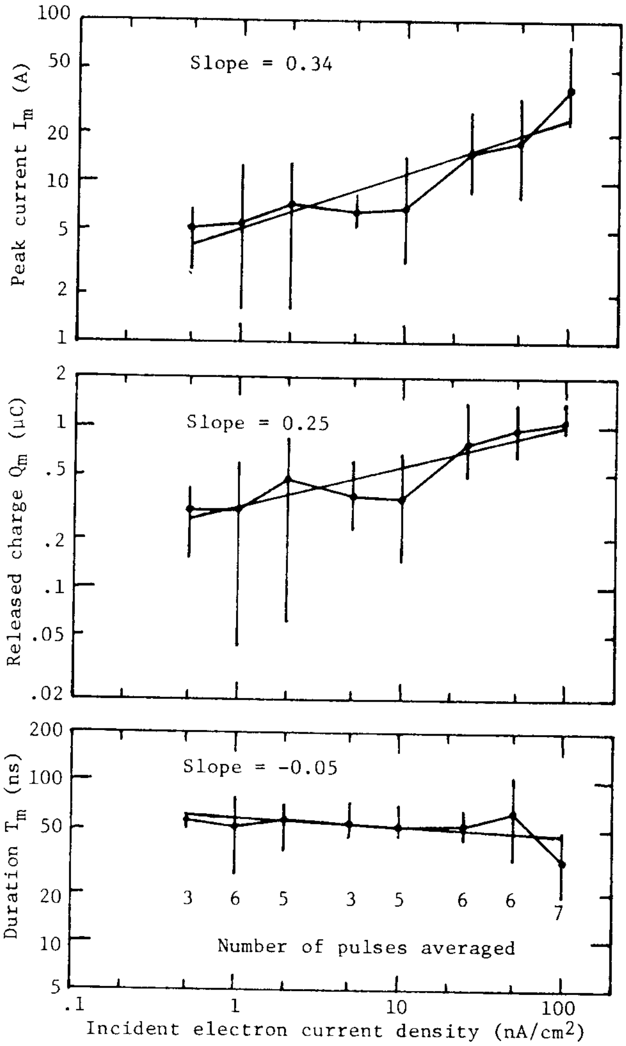

Fig. 3 Mask discharge current pulse properties for Kapton H. Beam energy = 20 keV, specimen area = 11.7 cm^2, specimen thickness = 50 μm.

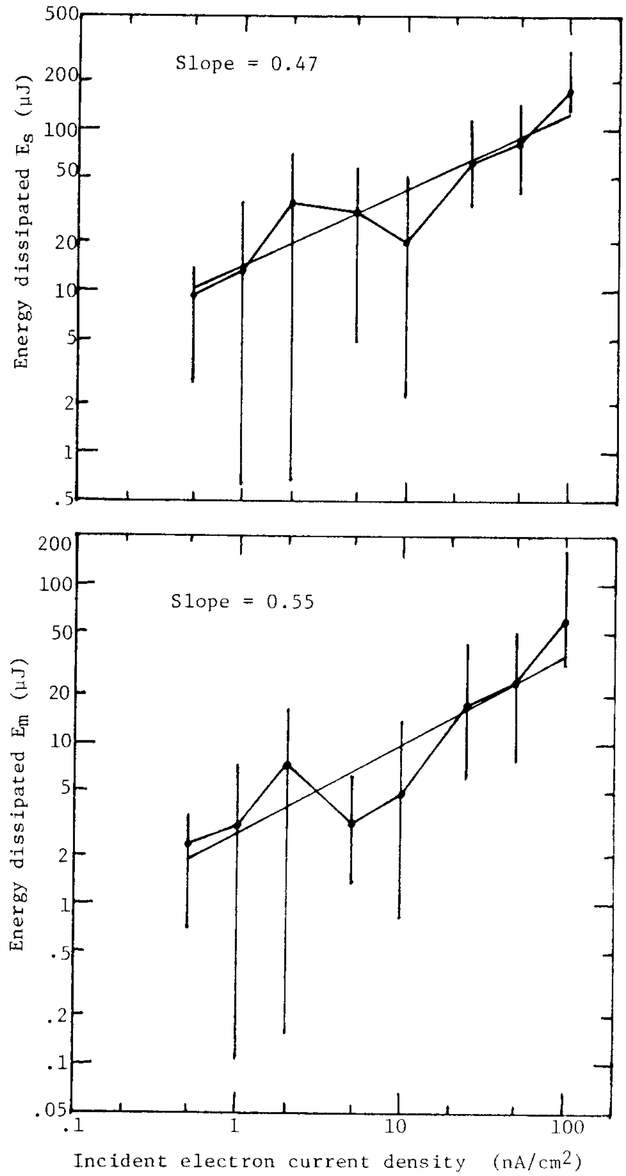

Fig. 4 Substrate (top) and mask (bottom) discharge energy dissipated in a 2.5 ohm resistor for Kapton H. Beam energy = 20 keV, specimen area = 11.7 cm^2, specimen thickness = 50 μm.

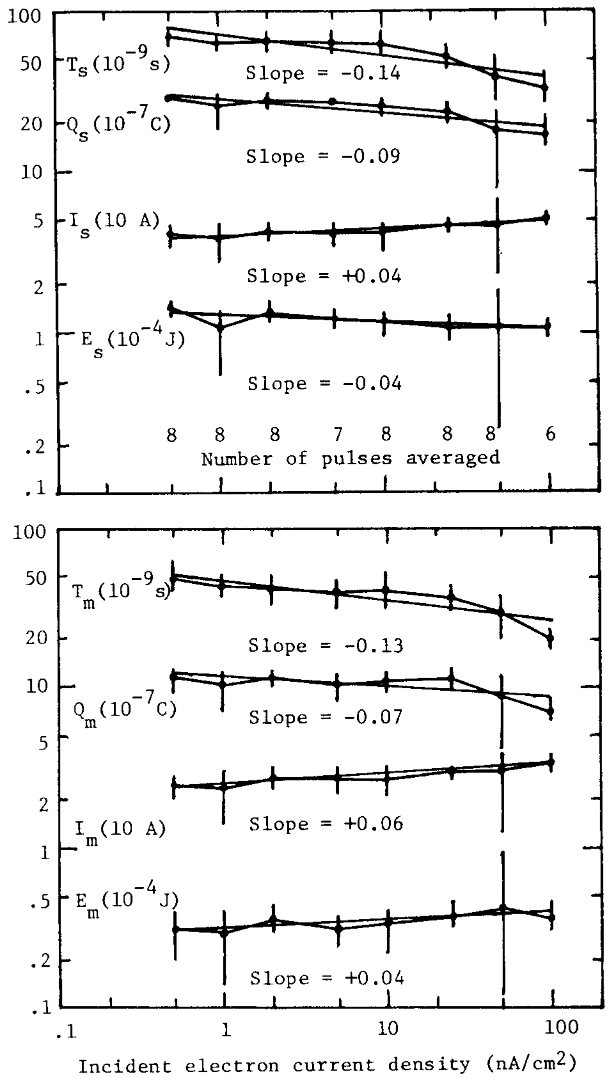

Fig. 5 Substrate (top) and mask (bottom) discharge pulse properties for Mylar. Beam energy = 20 keV, specimen area = 11.7 cm^2, specimen thickness = 75 μm.

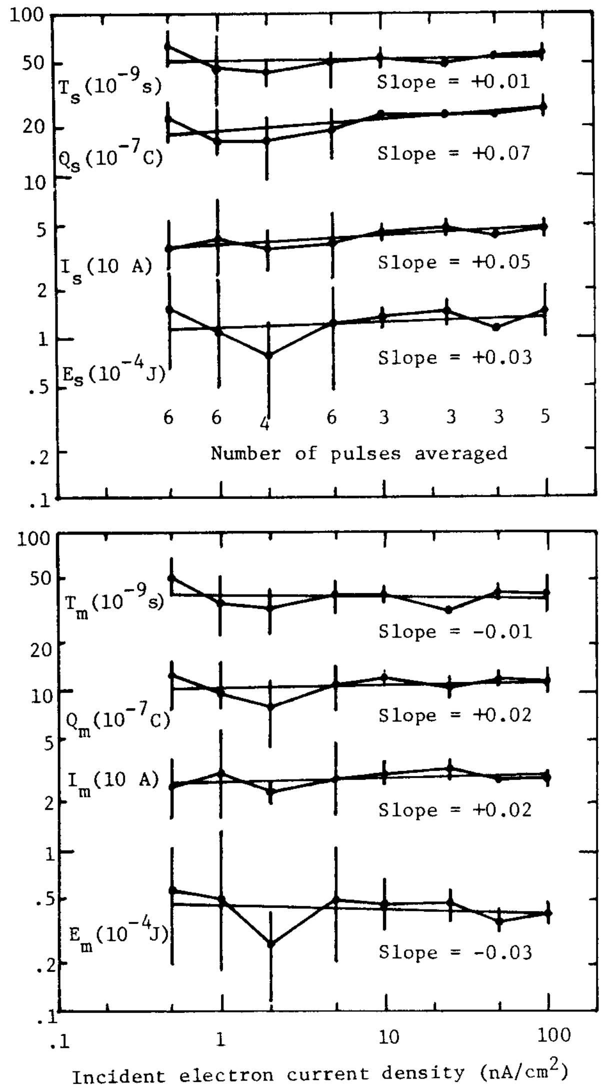

Fig. 6 Substrate (top) and mask (bottom) discharge pulse properties for FEP Teflon. Beam energy = 20 keV, specimen area = 11.7 cm^2, specimen thickness = 50 μm.

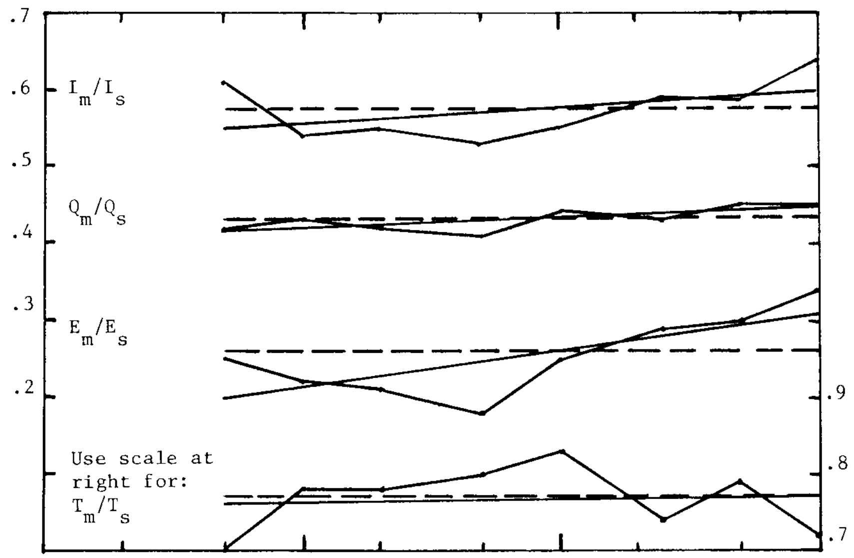

Fig. 7 Kapton H mask-to-substrate ratios. Dashed lines are averaged and solid lines are best-fit straight lines.

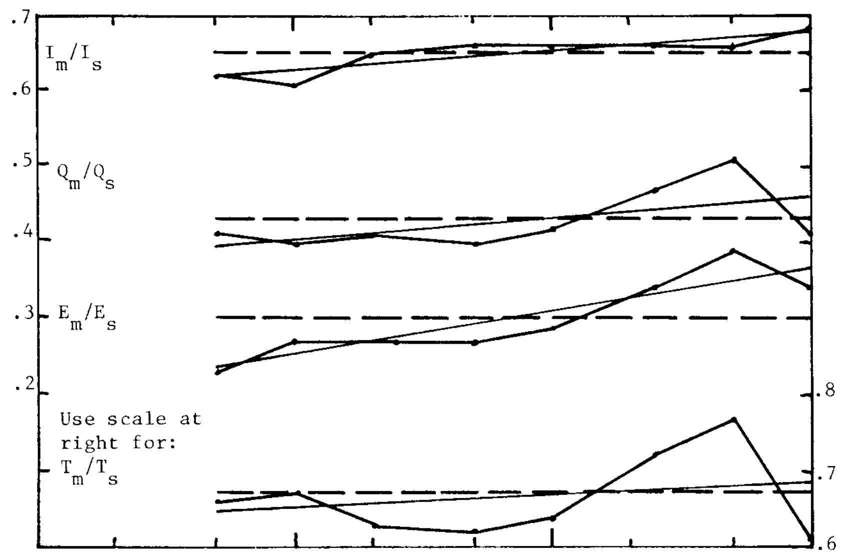

Fig. 8 Mylar mask-to-substrate ratios.

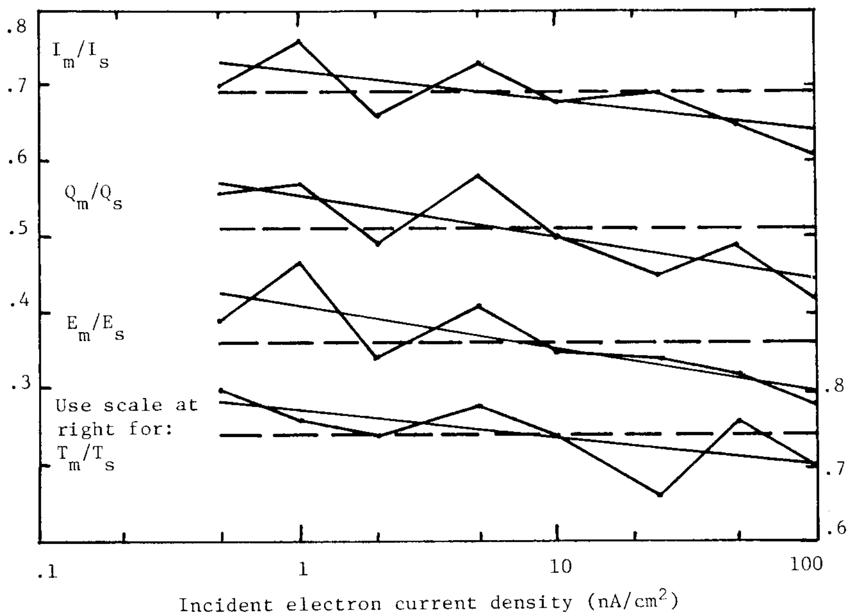

Fig. 9 FEP Teflon mask-to-substrate ratios.