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VARIATION OF MICROCHANNEL PLATE RESISTANCE WITH TEMPERATURE AND APPLIED VOLTAGE

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The resistance of microchannel plate electron multipliers is well known to be a function of both applied voltage and detector temperature. We show that the apparent variation of resistance with bias voltage is simply due to plate temperature increases resulting from resistive heating.

1. Introduction

Experimentally, it is well known that the resistance of a microchannel plate (MCP) is a function of both ambient temperature [1,2] (fig. 1) and applied voltage [3,4] (figs. 2–5). A knowledge of these variations is essential for the proper design of bias resistor chains for satellite borne channel plate X-ray detectors [2].

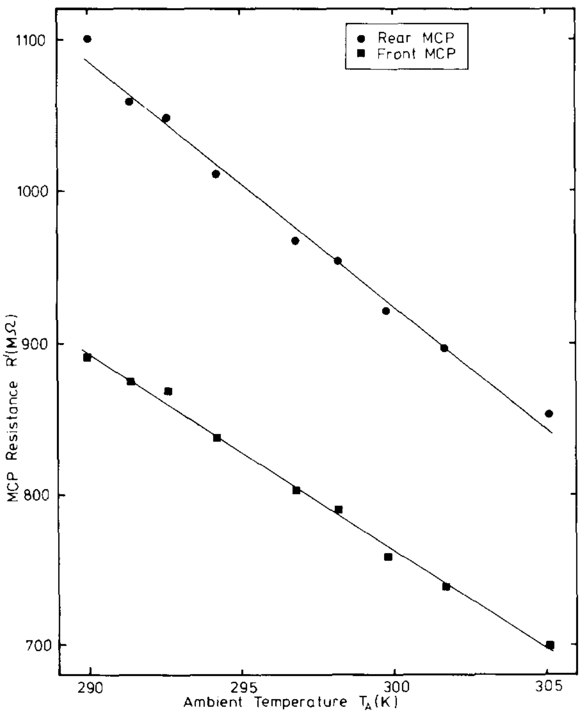

Fig. 1. Variation of MCP resistance with ambient temperature, at constant bias voltage (detector 4, table 1). Lines are least-squares straight line fits to the data. $V_F = 1600$ V, $V_R = 1700$ V, Front plate $\alpha = 0.0155$, rear plate $\alpha = 0.0153$.

The variation of resistance with temperature is a result of the physical properties of the MCP glass, which has bulk and surface resistivities of the form [1]

$$\rho = \rho_0 \exp(E/kT)$$

where ρ and ρ_0 are resistivities at absolute temperature T and at 0 K respectively, E is the activation energy of conduction (~ 0.06 eV at room temperature) and k is the Boltzmann constant.

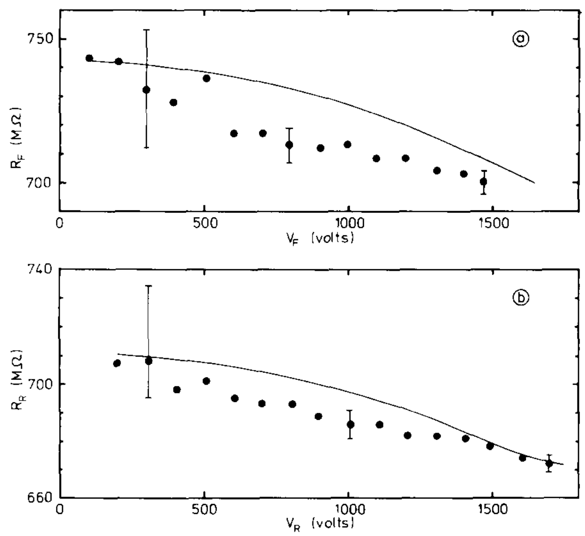

Fig. 2. Variation of MCP resistance with applied bias voltage, at constant ambient temperature, $T_A = 293$ K, detector 1. Typical error bars, derived from digitisation errors on measured current and voltage, are shown. Full curve: model prediction. (a) Front MCP, $R_0 = 742.6$ MΩ, (b) rear MCP, $R_0 = 710.7$ MΩ.

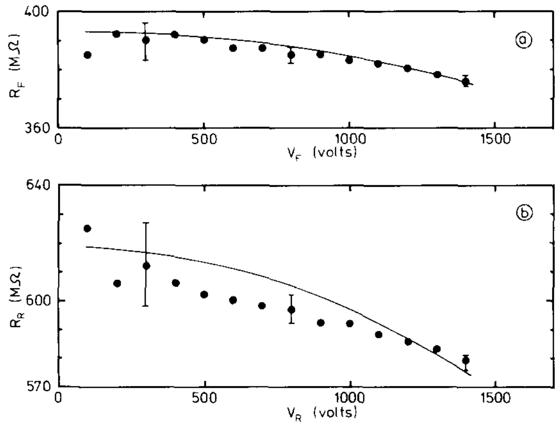

Fig. 3. As fig. 2. Detector 2. (a) Front MCP, $R_0 = 393.1$ MΩ, (b) rear MCP, $R_0 = 618.8$ MΩ.

Rager and Renaud [3] attributed the variation of MCP resistance with voltage to an electrolysis mechanism initiated by water vapour adsorbed on the channel surfaces. Their measurements showed a voltage dependence that became smaller with increasing time spent under vacuum, which is consistent with water vapour being gradually removed from the channel surfaces. Some voltage dependence, however, was still present after long periods of operation. We have now measured a dependence of resistance on bias voltage with MCPs which had been vacuum baked and operated continuously under vacuum (at pressures of $\sim 5 \times 10^{-6}$ mbar) for many weeks (figs. 2–5).

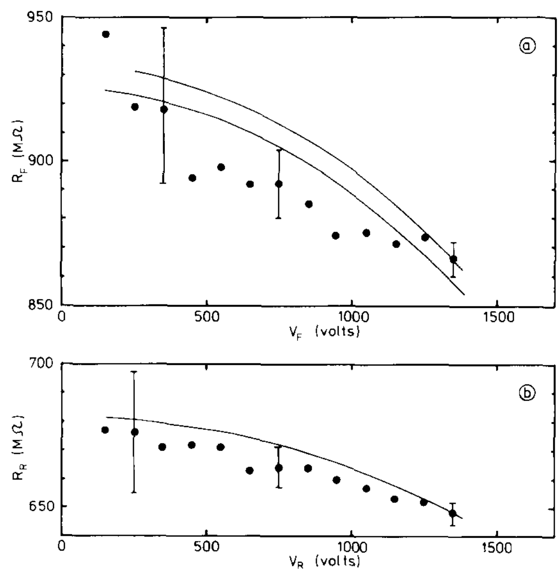

Fig. 4. As fig. 2. Detector 3. (a) Front MCP, $R_0 = 933.4$ MΩ (top curve), 925.0 MΩ (bottom curve); (b) rear MCP, $R_0 =$ 681.5 MΩ.

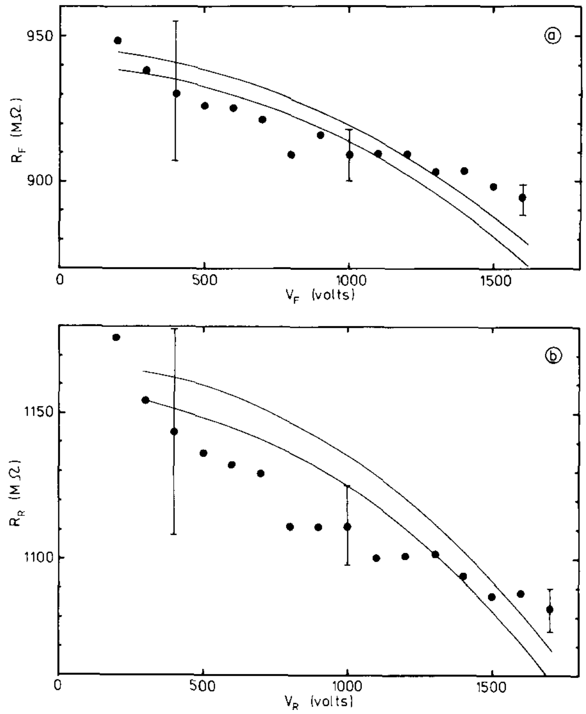

Fig. 5. As fig. 2 except $T_A = 291$ K. Detector 4. (a) Front MCP, $R_0 = 945.3$ MΩ (top curve), 939.4 MΩ (bottom curve); (b) rear MCP, $R_0 = 1166.8$ MΩ (top curve), 1156.3 MΩ (bottom curve).

We postulate that such persistent variations in resistance with bias voltage are simply a result of changes in temperature due to resistive heating of the MCPs.

2. Variation of MCP resistance

If our hypothesis is true then the MCP resistance, R, is a function of MCP temperature, T, only. The value of the MCP temperature will depend on the ambient temperature, T_A, and the heating effect of the applied bias potential difference, V. The most direct test of the hypothesis would be to measure R as a function of T, for a number of different values of V. This straightforward approach could not be used however, since it was not possible, with our present detectors, to measure the MCP temperature when bias voltages (up to 3.5 kV) were applied.

The alternative approach, adopted here, is to try and model the thermal behaviour of an MCP and hence predict its resistance as a function of ambient temperature and voltage, $R(T_A, V)$.

We will assume that the MCP resistance is a function of T only and construct a model which predicts the MCP temperature as a function of ambient temperature and bias voltage. The MCP resistance as a function of

V will then be predicted by a resistance–temperature relationship derived at constant bias voltage.

2.1. Constant bias voltage

For the restricted ambient temperature range of 290–305 K we may describe the measured variation in MCP resistance with ambient temperature, at constant bias voltage, by means of a temperature coefficient, α', defined by

$$R'(T_A) = R'_0[1 - \alpha'(T_A - 293)], \quad (1)$$

where $R'_0 = R'(293\ \mathrm{K})$.

Temperature coefficients were calculated from plots (e.g. fig. 1) of MCP resistance at constant bias voltage against ambient temperature. A least-squares straight line fit was calculated for each MCP, with the gradient of the line being equal to $\alpha' R'_0$.

The actual MCP temperature in this situation is given by

$$T = T_A + \delta T,$$

with δT being due to resistive heating. Over the ambient temperature range investigated we may assume that δT is constant if this does not alter the rate of heat loss from the MCP. Calculated values of δT are of order 4 K (sect. 4); the assumption δT = constant implies a change in the heat radiated from the MCP of 5% or less (sect. 3) over this temperature range. Eq. (1) may therefore be rewritten as

$$R(T) = R_0[1 - \alpha(T - 293)], \quad (2)$$

where $\alpha = \alpha'$.

Measurements of α were made on the MCPs of detectors 3 and 4 (table 1) and six other MCPs. No difference was found between MCPs with length to diameter ratios ($L:D$) of 80:1 and 120:1. The mean value of α did, however, depend on bias angle, 0.0144 for 0° bias plates and 0.0175 for 13° bias plates. These average values were used in modelling detectors 1 and 2.

Table 1
Model parameters and MCP characteristics. All MCPs have 12.5 μm diameter channels on 15 μm pitch. Front plate bias angle 0° and rear plate 13°. MCPs manufactured by Mullard Ltd, New Road, Mitcham, Surrey, CR4 4XY, England

Detector number	1	2	3	4
MCP outer diameter [mm]	36	55	36	36
$L:D$	120:1	120:1	80:1	120:1
d_1 [mm]	30	49	30	30
d_2 [mm]	30	1	30	30
d_3 [mm]	32	47	32	32
α front	0.0144	0.0144	0.0153	0.0155
α rear	0.0175	0.0175	0.0147	0.0153
ϵ front	0.2	0.2	0.08	0.2
ϵ rear	0.4	0.4	0.4	0.1

2.2. Constant ambient temperature

To determine R_0 in eq. (2) we need to measure the MCP resistance at a known MCP temperature. The only time the temperature is known is when $V = 0$, in which case $T = T_A$. By applying a least-squares straight line fit to the resistance data in figs. 2–5 and extrapolating to zero voltage we can find a value for $R(T_A)$. Given a value for α, R_0 can then be calculated from eq. (2). Considerable errors are present in measurements of R at low applied voltages because of digitisation errors in the measurement of current and voltage. The calculated values for R_0 are therefore uncertain and alternative predictions are made in figs. 4a, 5a and b where low voltage measurements depart from the overall trend.

3. Resistive heating model

The temperature of an MCP subject to a bias potential difference V, applied along the length of the channels, must rise above ambient until

$$\dot{Q}_T = V^2/R, \quad (3)$$

where $\dot{Q}_T$ is the total heat lost per second by the MCP. Since MCPs are operated under vacuum no heat will be lost by convection. The effect of conduction will be small in our detectors whose inner bodies are manufactured from Macor (a machinable ceramic) and will be confined to losses through electrode connections. Most of the heat loss will therefore be by radiation.

The Stefan–Boltzmann law for the heat radiated from one surface of a single, circular MCP, $\dot{Q}_S$, at a temperature T_S is of the form [5]

$$\dot{Q}_S = \pi d^2 \sigma \epsilon (T_S^4 - T_A^4)/4 \quad (4)$$

where ϵ is the effective thermal emissivity of the MCP, d the MCP diameter and σ Stefan's constant.

The surface temperature of the MCP is assumed to be uniform and to be a good representation of the MCP bulk temperature (according to the formula of Soul [5] actual centre to surface temperature differences should be of order 10^{-3} K).

Since all our results were obtained using two-stage "tandem" MCP detectors (fig. 6), four radiating surfaces (a, b, c, d) need to be considered in any detailed thermal analysis. Let the surface temperatures of the front and rear MCPs be T_F and T_R respectively. Surfaces a and d are assumed to radiate to the vacuum chamber at ambient temperature T_A, while surface b (temperature T_F) radiates to surface c (temperature T_R) and vice versa. Using eq. (3) we obtain the following description

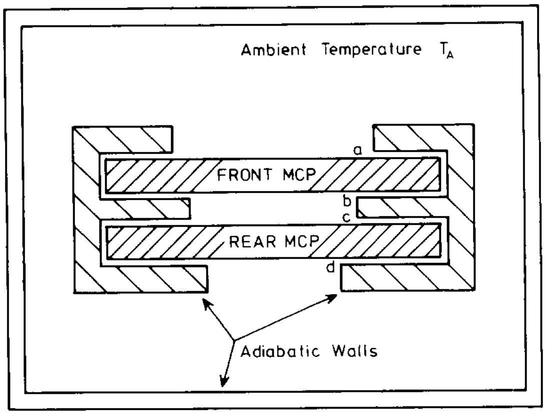

Fig. 6. Cross section of schematic detector on which the model is based. The diameters of the front (a), rear (d) and middle (b, c) radiating surfaces are d_1, d_2 and d_3 respectively. Front MCP temperature T_F, rear MCP temperature T_R.

of the thermal balance between the plates and their surroundings

$$\dot{Q}_S(a) + \dot{Q}_S(b) = V_F^2/R_F, \tag{5}$$

$$\dot{Q}_S(c) + \dot{Q}_S(d) = V_R^2/R_R, \tag{6}$$

where V_F and V_R are the bias voltages applied to the front and rear MCPs respectively and R_F and R_R are the respective resistances at these voltages. $\dot{Q}_S(r)$ is, of course, the rate of heat loss from surface r.

To solve eqs. (5) and (6) for T_F and T_R they must first be expanded using eqs. (2) and (4);

$$\lambda d_1 \epsilon_F (T_F^4 - T_A^4) + \lambda d_3 \epsilon_F (T_F^4 - T_R^4) = V_F^2 / \{ R_{0F}[1 - \alpha_F(T_F - 293)] \}, \tag{7}$$

$$\lambda d_2 \epsilon_R (T_R^4 - T_A^4) + \lambda d_3 \epsilon_R (T_R^4 - T_F^4) = V_R^2 / \{ R_{0R}[1 - \alpha_R(T_R - 293)] \}, \tag{8}$$

where $\lambda = \pi\sigma/4$. Given values for α, R_0 and ϵ for each plate (table 1) and assuming an initial value T_{R1} for T_R it is possible to find, numerically, a temperature T_{F1} for which eq. (7) is satisfied. Assuming $T_F = T_{F1}$ a temperature T_{R2} for which eq. (8) is satisfied can be found in a similar manner. A first approximation to the MCP resistances at ambient temperature T_A and with bias voltages V_F and V_R applied can then be calculated by substituting T_{F1} and T_{R2} into eq. (2).

The calculations are then repeated using $T_R = T_{R2}$ to calculate T_{F2} (eq. (7)) and $T_F = T_{F2}$ to calculate T_{R3} (eq. (8)). The iteration is continued until successive differences in calculated resistances are < 0.05 MΩ.

No measurements of the thermal emissivity, ϵ, of lead glass MCPs exist. This parameter was varied to produce a reasonable fit to measurements of $R(T_A, V)$. Nominal values of $\epsilon = 0.2$ for 0° bias MCPs and $\epsilon = 0.4$ for 13° bias plates have generally given good results (see sect. 4). These values seem physically reasonable given that the spectral emissivity of nichrome, the MCP surface electrode material, is approximately 0.35 [6] and is very dependent on surface condition. The difference between the 0° and 13° bias MCPs is attributed to the differing effective area of nichrome on each (open area 63%). A 13° bias plate will have a much higher contribution from the electrode which penetrates (~ 1 channel diameter) into the channel than will a 0° bias plate because in the former case the channel is not perpendicular to the surface.

4. Results

Four different tandem MCP detectors were modelled (table 1). The values of d_1, d_2, d_3 are the diameters of the actual radiating surfaces, which are normally defined by annular high voltage electrodes. The model predictions for $R(T_A, V)$ are plotted alongside the measured values in figs. 2–5 and in all cases they are in reasonable agreement.

Detector number 2 is a different design [7] to the other three in that the MCPs are effectively insulated at the rear by a resistive anode (manufactured from Macor, cf. sect. 2). This would imply a value of $d_2 = 0$ but for ease of modelling a nominal value of $d_2 = 1$ mm was used.

The best fit emissivity values used for two of the MCPs (table 1) are different from those given in sect. 3. The front plate of detector no. 3 bore a 14000 Å thick CsI photocathode and would thus be expected to have a different (smaller) value of ϵ. The best fit emissivity of the rear MCP of detector 4 is very low, $\epsilon = 0.1$ instead of $\epsilon = 0.4$. The reason for this is unknown, but it is interesting to note that this MCP alone had been extensively used before the present measurements were made.

The model consistently overestimates the MCP resistance (underestimates the MCP temperature) in the 300–1000 V region. This may be due to the simplicity of the model or may be caused by poor contact conditions between the electrode and the MCP surface. Very large changes in resistance with bias voltage have been observed when the electrical contact to the MCP surface

Table 2
Calculated temperature rise above ambient ($T - T_A$) for highest applied voltage modelled

Detector	1	2	3	4
Front MCP [K]	3.4	3.2	4.8	4.7
Rear MCP [K]	3.1	4.0	3.4	5.6

was so poor that breakdown occurred before operating voltages were achieved.

In figs. 4a, 5a and b the model underestimates the MCP resistance (i.e. overestimates the temperature) at high operating voltages. It can be seen from table 2 that these three MCPs have the greatest calculated difference from ambient temperature. In this situation the assumption that no heat is lost by conduction may no longer be true. A reduction in calculated temperature, T, of only 0.5–1.0 degrees is all that is required for the model to become a good fit to the data.

5. Conclusions

We have demonstrated that the variation in MCP resistance with applied bias voltage can be explained by the change in MCP resistance due to the temperature rise caused by resistive heating. By far our greatest uncertainty is in the values of the MCP emissivity, but while the range of values used is large, all are physically reasonable.

The maximum calculated temperature differences shown in table 2 highlight the need to ensure a stable thermal environment for a detector which is powered via a resistive divider chain [2]. Fluctuations of order 2 K in individual MCP temperatures could significantly affect the applied bias voltage (and hence the MCP gain and quantum efficiency) through changes in the MCP resistance.

Acknowledgements

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