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Paschen Curve Analysis to Optimise Pulsed D.C Sputtering Plasmas

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INTRODUCTION & EXPERIMENTAL SETUP

The behaviour of the breakdown voltage of a pulsed d.c. magnetron sputtering system (PDMS) under various operating conditions has been studied with reference to Paschen's Law [1].

This work is a preliminary study of the effect of the working pressure, operating current , frequency and target-to-substrate distance on the breakdown voltage of an Ar-Cu pulsed dc magnetron discharge.

In the discharge, the voltage initially increases to -650 V but after 2.5 μs it stabilises at -450V for the remaining pulse-on time, producing a stable plasma. This voltage is taken as the breakdown voltage.

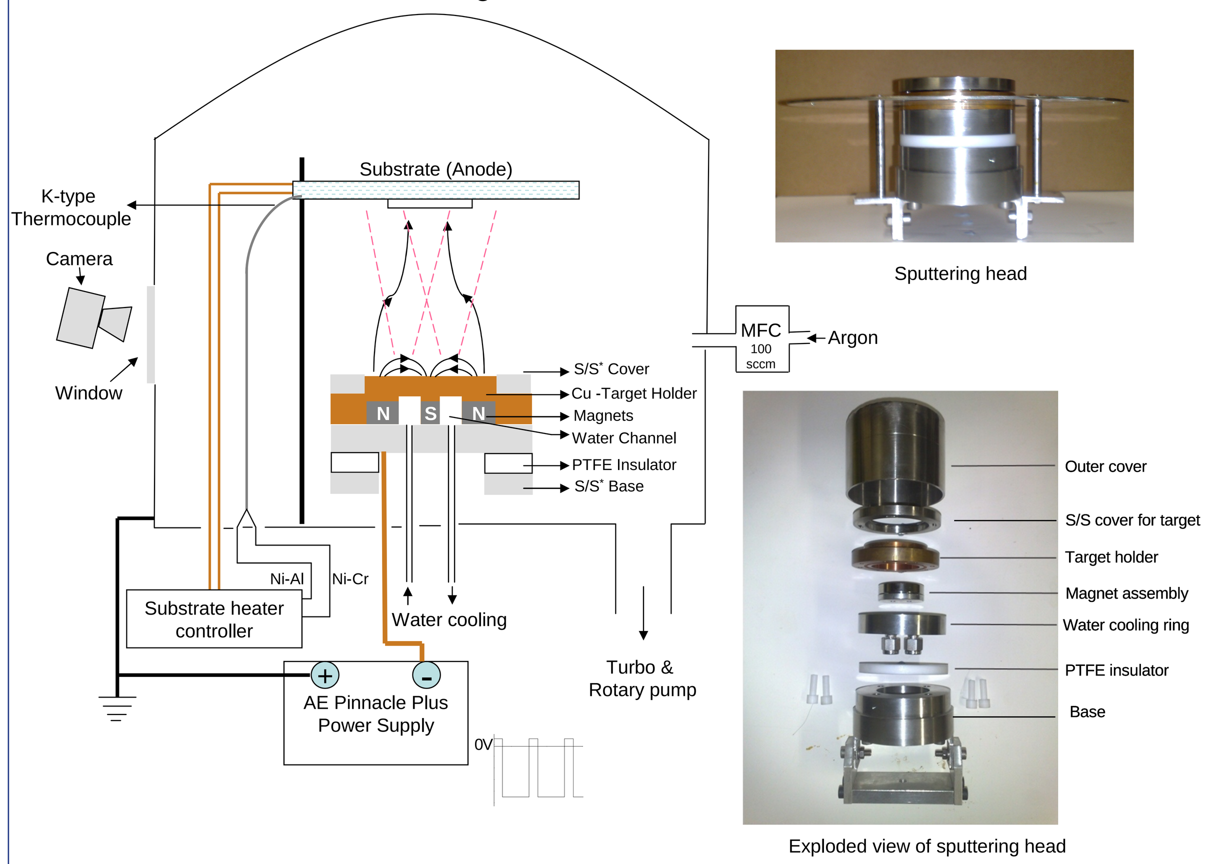

Figure 1 Schematic of Pulsed D.C Magnetron Sputtering System

RESULTS AND DISCUSSION

1. The behaviour of breakdown voltage with current at d.c.

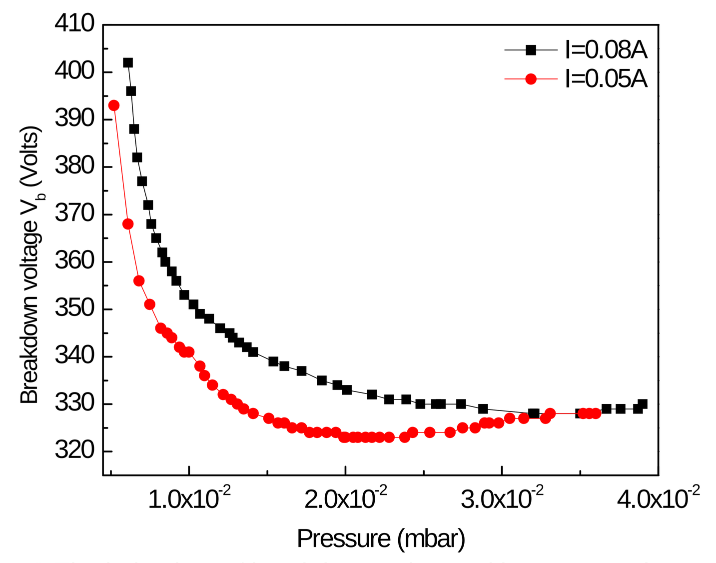

Figure 2 *The behaviour of breakdown voltage with current at d.c.*

The breakdown voltage decreases with increasing pressure in constant current mode, and at a certain pressure it reaches a minimum value and then increases thereafter exactly as Paschen explained in his work .

The pressure at which the minimum breakdown voltage occurs shifts towards higher pressure when the operating current is increased for electrode separations of *d* = 10 cm (Figure 2) and *d* = 6 cm (not shown).

2.The behaviour of breakdown voltage with pressure at constant current and different frequencies.

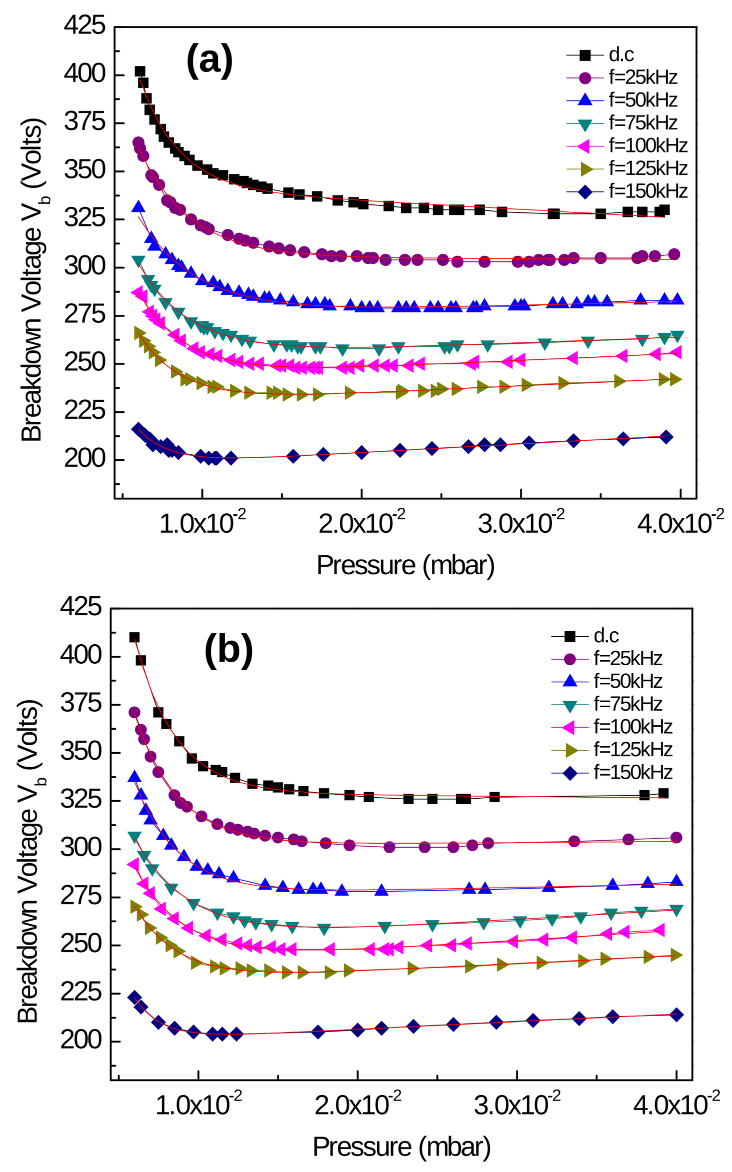

Figure 3 Behaviour of breakdown voltage at different pressures at I= 0.08 A , τ_{off} = 1μs, d =10 cm (a) and d= 6 cm (b).

The breakdown voltage (V_b) decreases when the frequency increases. This is caused by the pre-breakdown current produced by the remaining metastable atoms and ions from the previous cycle [2,3].

The breakdown voltage minima shift towards lower pressures with increase in frequency. This could be due to the combined effect of higher mean free path (at low pressure) and short pulse-on time (at high frequency)

Different fitting models have been tried but the results obtained from the experiments follow an exponential linear relationship:

$$V_b = Ae^{-\frac{p}{B}} + C + Dp$$

Where *p* is pressure and *A*,*B*,*C* and *D* are constants

The red line (Figure 3) shows the exponential linear fit. There could also be some other functions that fit this data but the good experimental agreement with this exponential linear relationship suggests that the decrease in breakdown voltage is of the form of an exponential function and the increase in the breakdown voltage on the right hand side is of linear form. A possible explanation is due to the different electrode geometry, restricted operating pressure range, the pulsed d.c. supply, properties of the target, etc.

The pressures at which minimum values of breakdown voltage occur are calculated from the fitted curve and are independent of the electrode separation (Figure 4).

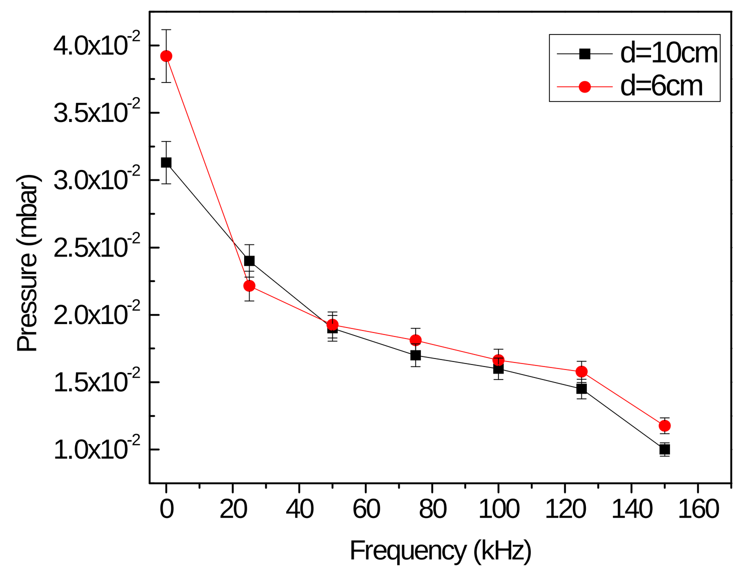

Figure 4 The value of pressure at breakdown minimum plotted against operating frequency.

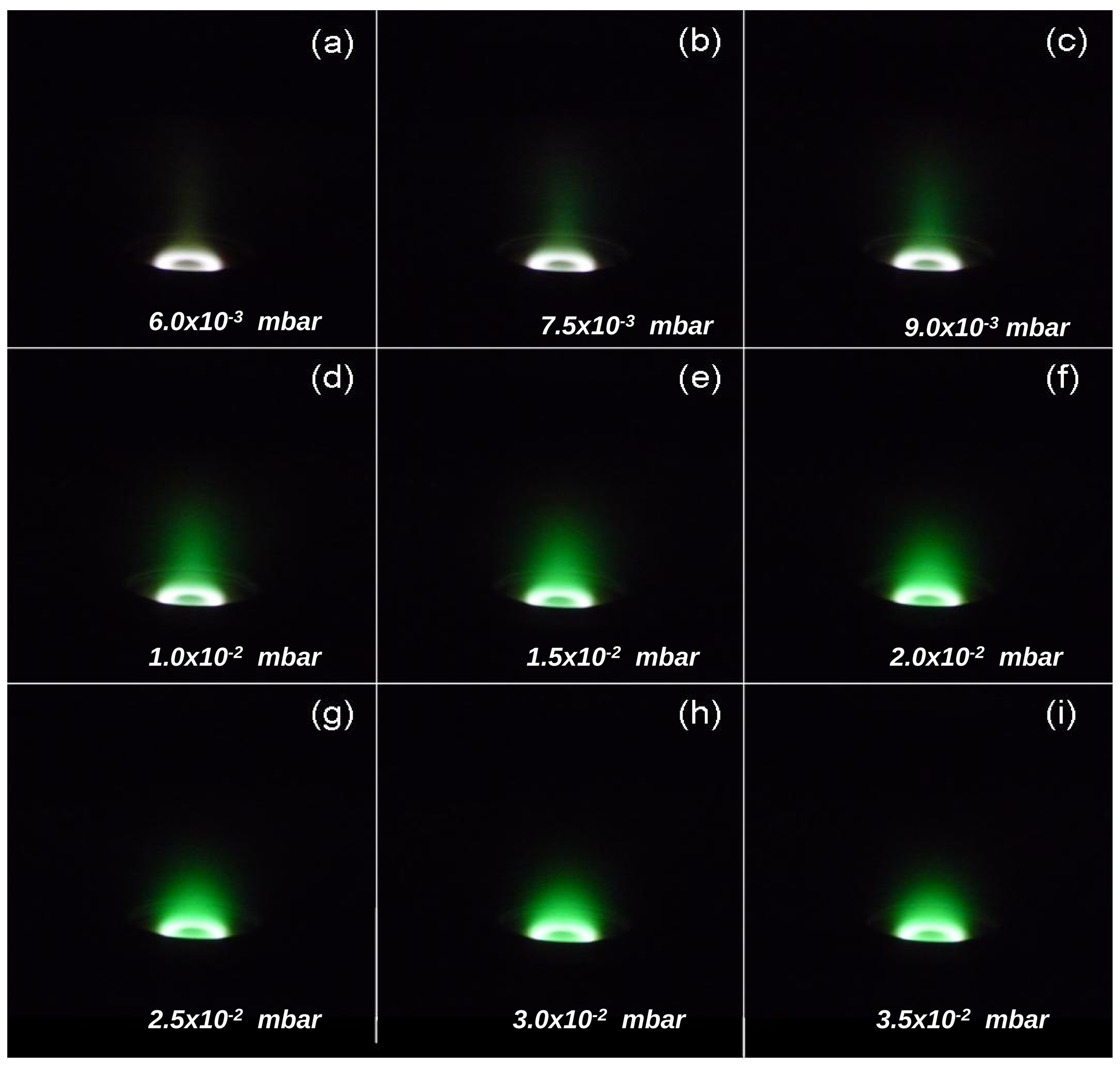

Figure 5 Changes in the Ar- Cu plasma discharge density at various operating pressures .

A prominent plasma colour change from purple to green was noticed between 6.0 x 10^{-3} mbar and 1.0 x 10^{-2} mbar

The plasma shape changed above 1.0 x 10^{-2} mbar to a semi-circular form. The diameter of the semi circle reduced when the pressure reached 3.5 x 10^{-2} mbar. This could be due to the reduction in the mean free path with increase in pressure.

3 Variation in breakdown voltage with pulsing frequency at different pressures and constant pulse-off time.

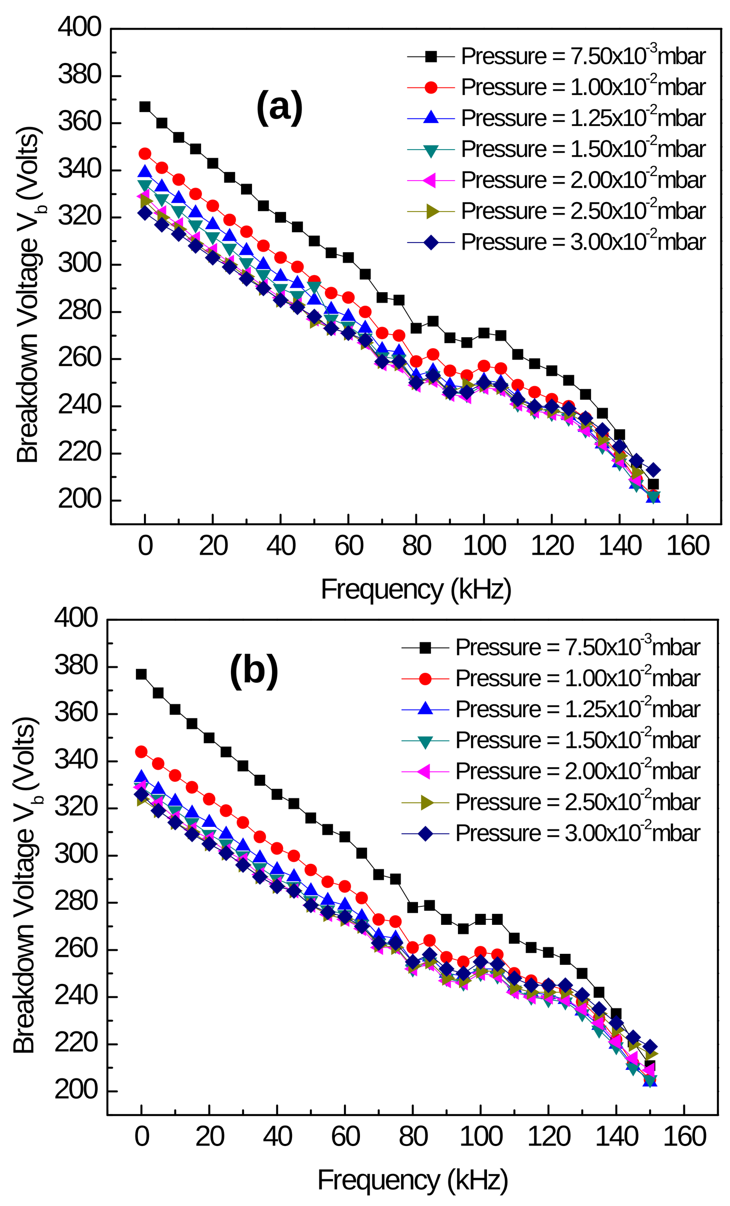

Figure 6 Behaviour of breakdown voltage with pulsing frequency at different pressures and constant pulse off time τ_{off} =1 μs at d = 10 cm (a) , d = 6 cm (b).

The breakdown voltage decreased consistently as frequency increased up to 70 kHz but there was a perturbation of this consistent behaviour from 70 kHz to 130 kHz.

As the pressure increased there was a slight change in the position of the perturbation towards a higher frequency in both cases.

The excitation energy and ionization energy of argon are 11.7 eV and 15.7 eV respectively and the work function for copper is 4.4 eV. So the internal energy of the metastable atoms and remaining ions from the previous cycle is greater than twice the work function energy**.** Hence more secondary electrons will be created in addition to neutralisation [3]. It means that an increase in frequency will increase the pre breakdown current .

This pre-breakdown current at a short pulse-on time can cause a distortion in the field. Hence a small perturbation can be expected in the breakdown voltage while increasing the operating frequency.

4 Variation of breakdown voltage with pulsing frequency at constant pressure and different operating currents

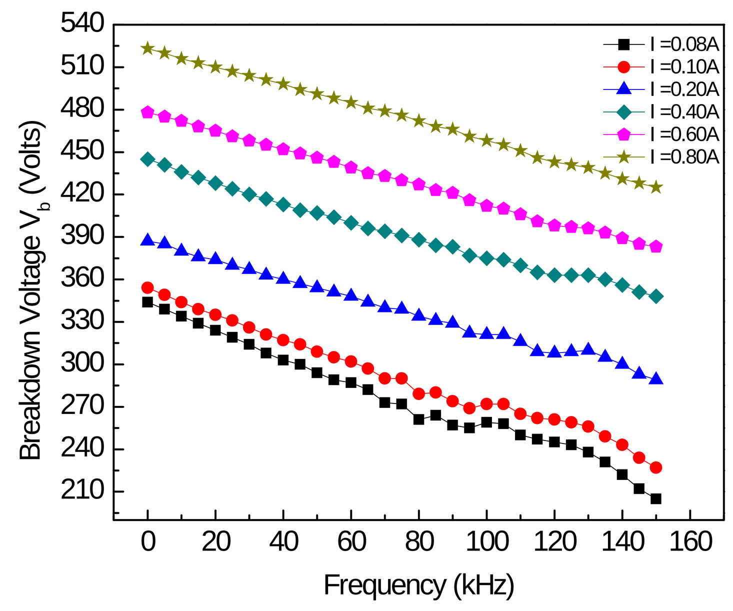

Figure 7. Breakdown voltage with pulsing frequency at different operating currents I from 0.08 A to 0.80 A at constant pressure of 1x10^{-3} mbar and pulse off time τ_{off} of 1 μs at d = 6 cm.

When the operating current increases the breakdown voltage increases**.** The effect of the perturbation due to pre-breakdown current can be suppressed by increasing the operating current. The pre-breakdown current is of the order of mA.

5 Variation of breakdown voltage with pulsing frequency at constant pressure and different pulse-off times.

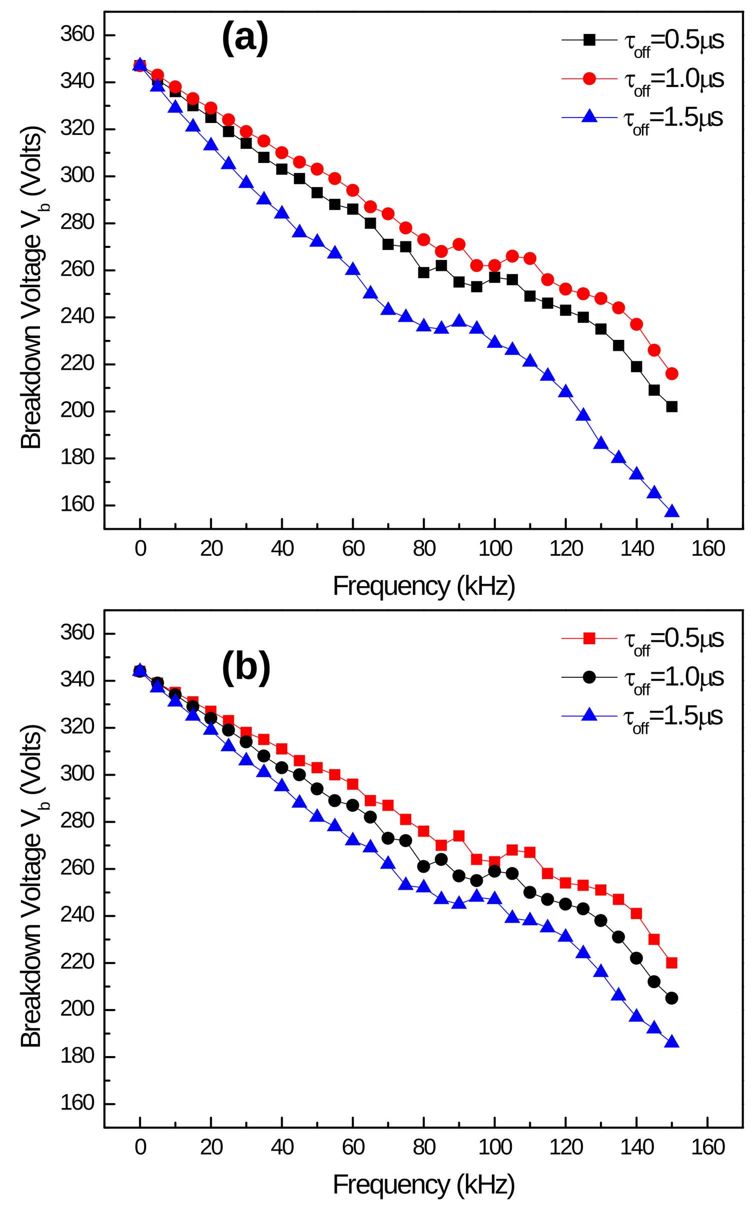

Figure 8. Behaviour of breakdown voltage with pulsing frequency at constant pressure of 1.0x10^{-3} mbar and different pulse off times off of 0.5 μs, 1.0 μs and 2.0μs at d=10cm (a) d = 6 cm (b).

At a constant frequency the increase in τ_{off} causes decreases in τ_{on} and hence will decrease the rate of formation of ions and secondary electrons.

A proposed explanation is that the greater number of metastable atoms from the previous cycle can produce a pre-breakdown current. There will be a rise in the pre-breakdown current during the first few microseconds of the next pulse. Increasing τ_{off} will decrease τ_{on} and hence generate more disturbances in the field for short pulse-on times that can lead to a decrease in the breakdown voltage

CONCLUSION

Paschen curves showing the behaviour of breakdown voltage with different operating parameters of a pulsed d.c. magnetron sputtering system have been studied.

In constant current mode, the breakdown voltage decreases with increase in pressure and at a certain pressure it reaches a minimum value and then increases thereafter.

When current is increased the breakdown voltage increases and the minima shift towards the higher frequency region.

The breakdown voltage decreases and the minima shift towards the lower pressure region when the frequency is increased.

The pressure at which the minimum breakdown occurs is independent of the electrode separation.

A steady decrease in breakdown voltage with increase in frequency at constant pressure is perturbed between 70kHz and 130kHz due to pre-breakdown current.

The effect of pre-breakdown current may be suppressed with an increase in the operating current.

Breakdown voltage was found to decreases with increase in pulse off time at constant frequency.

These results are important when vacuum is used as an insulating medium and also when a pulsed d.c. supply is used as a power source for breakdown.

The basic study of these parameters can help to produce a stable breakdown at low voltage and hence improve the sputtering performance and target life.

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