Borocarbon nitride (BCN) films were prepared by reactive magnetron sputtering from a \( \text{B}_4\text{C} \) target and deposited to make metal-insulator-metal (MIM) sandwich structures using aluminum as the top and bottom electrodes. BCN films were deposited at various \( \text{N}_2/\text{Ar} \) gas flow ratios, substrate temperatures. The electrical characterization of the MIM devices includes capacitance vs. voltage (C-V), current vs. voltage, and breakdown voltage characteristics. The above characterizations were performed as a function of deposition parameters. By varying the nitrogen concentration in the deposited films and substrate deposition temperatures, the electrical properties of BCN can be tuned accordingly. BCN films having dielectric constant as low as 2.13 with high dielectric breakdown strength of 3.4 MV/cm and resistivity of \( 3 \times 10^{12} \Omega \cdot \text{cm} \) were achieved.

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substrate were loaded in the sputtering system to deposit BCN films. To measure the film thickness, a glass slide was used as a control substrate. A black marker line of 2 mm wide was drawn on this control substrate. After depositing the required film, the black marker line was etched away with acetone dip to leave a step in the middle. The target is placed facing the substrate holder at an angle of 45°. The rotation speed of the substrate was set around 20 rpm to get uniform films. The sputtering duration was kept 1 hour for all the samples. The thickness measurements of BCN films were done by Veece Dektak 150 Profilometer on the step in the control substrate. The BCN thicknesses ranged from 900 Å–2000 Å. Finally, five aluminum strips of 3 mm width each running perpendicular to the back electrode were deposited on the BCN layer to form the top electrode of the MIM structures.

Current-Voltage (I-V) measurement was performed on MIM devices by using HP 4145B semiconductor parameter analyzer. This was also used to measure the resistivity and breakdown voltage of the BCN films. The surge of 1 mA current is considered as the electrical breakdown condition for the films. The dielectric breakdown strength was calculated by knowing the thickness. The capacitance was measured by using HP 4275A Multi-Frequency LCR meter at 1 MHz frequency. The dimension of overlapping electrodes was found to be 3 mm × 3 mm and hence its effective area was 9 mm² and the film thickness gives the distance between the electrodes of MIM capacitor. By knowing the area of the overlapping electrodes and the film thickness, the dielectric constant was calculated.

Parasitic compensation was taken care before each capacitance measurement. A self-test was performed before every running to ascertain the instrument’s proper running. Measurement of HP test cable compensated for electrical length that is 1 m length to minimize the parasitic capacitance. The switch was set to facilitate the measuring bridge circuit to its optimum balance and for minimizing incremental measurement errors when standard test leads were used. A 1 m position was used as this was the standard leads. When the switch is set to its 1 m position, compensation is appropriately made for high frequency measurements for any propagation loss and phase errors in test leads.

Atomic compositions of the BCN films were found by XPS analysis. XPS was performed using a PHI 5400 ESCA system. The base pressure during analysis was 10⁻⁹ Torr. The Mg Kα X-ray source (hv = 1253.6 eV) at a power of 350 watts was used for the analysis. Although care was taken to minimize the exposure time in air, the atmospheric exposure could not be completely avoided. Both the survey and the high-resolution narrow spectra were recorded with electron pass energy of 44.75 eV and 35.75 eV, respectively, to achieve the maximum spectral resolution. Any charging shift produced by the samples was carefully removed by using a B.E. scale referred to C 1s B.E. of the hydrocarbon part of the adventitious carbon line at 284.6 eV. The C 1s peaks located at 286–286.9 eV are due to the presence of C-N bonds. Any surface contamination from ex-situ transfer was removed by Ar⁺ ion beam sputtering to minimize the adventitious carbon and oxidation. The concentration of oxygen was found to be less than 5% due to ex-situ XPS measurement and hence the atomic concentration of B, C and N are normalized with respect to oxygen. Non-linear least square curve fitting was performed using a Gaussian/Lorentzian peak shape after the background removal.

### Results and Discussion

The normalized atomic concentrations of boron, carbon and nitrogen were calculated. Table I shows the variation of boron, carbon and nitrogen concentrations in the film with different deposition temperatures. Table II shows the variation of boron, carbon and nitrogen concentrations with respect to the increase in N₂/Ar gas flow ratios.

| Substrate Temp. | Boron (at. %) | Carbon (at. %) | Nitrogen (at. %) |
|-----------------|--------------|---------------|-----------------|
| 25°C            | 34           | 40            | 26              |
| 300°C           | 36           | 31            | 33              |
| 500°C           | 40           | 24            | 36              |

Table II. Relative surface atomic concentration of boron, carbon and nitrogen as a function of N₂/Ar flow ratio from XPS analysis.

| N₂/Ar Ratio | Boron atomic concentration (%) | Carbon atomic concentration (%) | Nitrogen atomic concentration (%) |
|-------------|-------------------------------|-------------------------------|----------------------------------|
| 0.25        | 29                            | 38.4                          | 32.7                             |
| 0.50        | 30.3                          | 33.7                          | 36                               |
| 0.75        | 29.5                          | 31.5                          | 39                               |
| 1           | 29                            | 30                            | 41                               |

N₂/Ar = 0.75 and there is a small increase in the deposition rate at N₂/Ar > 0.75 for all deposition temperatures. The decrease in the rate can be attributed to the fact that the increase in the nitrogen gas in the sputtering ambience decreases the effective sputtering yield and hence results in a lesser deposition rate. When the N₂/Ar flow ratio increases above 0.75, the deposition rate slightly increases because, the rate of formation of BCN is favored more due to chemical reaction than the decreasing sputtering yield due to nitridation. As we can see in the Table II, the nitrogen concentration is at its highest for R = 1 and hence nitrogen is favorably bonding with carbon and hence explains slight increase in deposition rate.

Dielectric constant vs. deposition temperatures.— Figure 2 shows the variation of dielectric constant as a function of substrate deposition temperatures at various gas flow ratios. The dielectric constants of the samples tend to decrease with increasing temperature. It is reported in the literature that the increase in deposition temperature decreases the concentration of carbon in the BCN film. According to the values given in the Table I, the concentration of nitrogen is highest and the concentration of carbon is lowest around 500°C. It has been reported that dielectric constant of B₄C is around 4.8 to 8. The lowest value of dielectric constant of BN was found to be 2.2 by Plasma Assisted Chemical vapor deposition (PACVD). Hence the BCN thin film shows more of BN characteristics at higher temperatures and B₄C characteristics at lower temperatures respectively, thereby having

![Figure 1](image-url)  
**Figure 1.** Effect of N₂/Ar gas flow ratio on deposition rates.
lower dielectric constant at higher deposition temperatures and higher dielectric constant at lower deposition temperatures.

From the optical transmission studies on the film, the refractive indexes were calculated. The refractive index of the films deposited at different substrate deposition temperatures was found to decrease with increase in substrate deposition temperature as shown in Figure 3.

Dielectric constant vs. gas flow ratios.—Figure 4 shows the plot of dielectric constant vs. $N_2/Ar$ gas flow ratios at different deposition temperatures. The plot shows a decreasing trend of dielectric constant with the $N_2/Ar$ gas flow ratio till $N_2/Ar = 0.75$ and then shows an increasing trend at the end. This shows an increase in concentration of nitrogen for gas ratio from $N_2/Ar = 0.25$ till $N_2/Ar = 0.75$ and there is a negligible change after that per the values given in the Table II. The increase in the dielectric constant at $N_2/Ar = 1$ can be attributed to the fact that there is an increase in the deposition rate at $N_2/Ar = 1$ and therefore there is an increase in the film thickness. This increase in the film thickness gives rise to increase in the dielectric constant may be due to the formation of low dielectric constant interface layers adjacent to the electrode in the thinner films. This dominates the capacitance of the film. It can also be due to the degradation of the film quality when the film becomes thinner. Hence thinner films have lower dielectric constants.\textsuperscript{29,30}

I-V characterization.—Figure 5 shows the I-V characteristics at different substrate deposition temperatures per unit area. The leakage current density increases with increase in substrate deposition temperatures. Figure 6 shows the I-V characteristics at different $N_2/Ar$ gas flow ratios per unit area. The leakage current density decreases with increase in $N_2/Ar$ gas flow ratios. This implies that incorporation of nitrogen in the film increases the resistance to leakage current.

Resistivity vs. deposition temperatures.—Figure 7 shows the plot of resistivity vs. deposition temperatures at different $N_2/Ar$ gas flow ratios. From the figure below, we can see that the resistivity values tend to increase with increase in temperature and then start to decrease at 400 °C. According to Table I, the nitrogen and carbon concentrations are increasing and decreasing respectively with increase in
deposition temperatures. The electrical resistivity is found to increase with decrease in the carbon concentration in the film. Beyond 400°C temperature there is decreasing trend in resistivity for all the gas ratios. This may be due to the possible diffusion of aluminum into the BCN film, thereby decreasing the resistivity of the film.

**Resistivity vs. N₂/Ar gas flow ratios.**—Figure 8 shows the plot of resistivity vs N₂/Ar gas flow ratios at different deposition temperatures. The plot shows an increasing trend of resistivity with the N₂/Ar gas flow ratio till N₂/Ar = 0.75 and then shows a decreasing trend at the end. Table II shows the variation of carbon and nitrogen concentrations with respect to the increase in N₂/Ar gas flow ratio. This shows an increase of nitrogen concentration in the film for gas ratios from N₂/Ar = 0.25 till N₂/Ar = 0.75 and there is a decreasing trend afterwards. More the nitrogen content and lesser the carbon content may bring the characteristics of BN at higher N₂/Ar gas ratios. BN being an insulator has higher resistivity. The decrease in resistivity at N₂/Ar = 1 can be explained by the complex expression of the relative permittivity. In a lossy medium, a relative permittivity (dielectric constant) can be broken down into real and imaginary part.

\[ \varepsilon_r(\omega) = \varepsilon'_r(\omega) + i\varepsilon''_r(\omega) \]

Dielectric conductivity \( \sigma \) (units S/m, siemens per meter), which sums over all the dissipative effects of the material may represent an actual electrical conductivity caused by migrating charge carriers. The dielectric constant is related directly to conductivity. In the Figure 3, as the dielectric constant shows an increasing trend at N₂/Ar = 1, the corresponding conductivity also increases, hence this shows a decrease of resistivity at N₂/Ar = 1.

**Dielectric breakdown strength vs. N₂/Ar gas flow ratio.**—Figure 9 shows the variation of dielectric breakdown strength (DBS) as a function of N₂/Ar gas flow ratios at different deposition temperatures. Breakdown Strength shows an increasing trend with the increase in N₂/Ar gas flow ratios from N₂/Ar = 0.25 to 0.75, but has a decreasing trend in the end. The DBS of a-BN was found out to be around 2.2 MV/cm\(^2\) and the DBS of B₄C was around 0.1 MV/cm. The DBS

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**Figure 6.** I-V characteristics at different gas flow ratios per unit area.

**Figure 7.** Effect of deposition temperature on Resistivity.

**Figure 8.** Effect of N₂/Ar gas flow ratio on Resistivity.

**Figure 9.** Effect of N₂/Ar gas flow ratio on Dielectric breakdown strength.
higher DBS. boron concentrations leading to more BN phases in the film giving nature. As observed in Table I, there is an increase in the nitrogen and strength shows an increasing trend with increase in deposition temper-
sputtering from B_4C target in argon and nitrogen ambient. Electri-
crease in substrate temperatures. The characteristics of BCN film tend
increase in nitrogen in the BCN film and it also decreases with the in-
trend may be due to the increase in the thickness of the deposited film
be the defects, asperities and lesser will be its thermal conductivity.
lowered the field strength eventually lowering the DBS. 33
Dielectric breakdown strength vs. temperature.— Figure 10 shows the plot of dielectric breakdown strength as a function of deposition temperatures for different N_2/Ar gas flow ratios. Dielectric breakdown strength shows an increasing trend with increase in deposition temperature. As observed in Table I, there is an increase in the nitrogen and boron concentrations leading to more BN phases in the film giving higher DBS.

Conclusions

BCN thin films were deposited successfully by RF magnetron sputtering from B_4C target in argon and nitrogen ambient. Electrical characteristics are strongly dependent on the N_2/Ar flow ratios and deposition temperatures. The dielectric constant decreases with increase in nitrogen in the BCN film and it also decreases with the increase in substrate temperatures. The characteristics of BCN film tend more toward BN phases when the nitrogen concentration increase. The resistivity of the film and the dielectric breakdown strength increases with increase in N_2/Ar flow ratio and also with the substrate temperature. By having the required N_2/Ar flow ratios and deposition temperatures it is possible to achieve the required BCN films for various applications. Studies conducted revealed that BCN films can be potential low-k materials for inter dielectric layers for ULSI applications.

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