# Structural, Optical and Electrical Properites of Quaternary Hafnium-Aluminium Zinc Oxide Films Grown by Atomic Layer Deposition for Transparent Conductive Oxide Applications

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Transparent Conductive Oxide (TCO) films are characterized by having simultaneously exceptional electrical conductivity and high transmission in the visible range. Among many TCO materials, doped zinc oxide (ZnO) is one of the foremost candidates for next generation electronic devices, since it exhibits several desirable optoelectrical properties, in particular direct and wide bandgap (~3.37 eV), high carrier concentration exceeding $10^{19}$ $cm^{-3}$ and very low resistivity in the range of $10^{-3}$ Ωcm. These properties may be finely tuned and enhanced by doping elements to create an oxide alloy. Despite the vast range of papers covering the properties of singly-doped ZnO, there is still undiscovered potential of simultaneous doping ZnO with two elements, creating a quaternary material. During our studies we fabricated a co-doped ZnO films with both aluminum and hafnium atoms (HAZO), utilizing atomic layer deposition technique (ALD). This method offers a precise control of the film thickness due to self-limiting character of the reactions during every half-cycle along with unraveled conformality and uniformity of the grown films. The optical, electrical and structural properties of the samples were investigated for varying Hf and Al concentrations to establish a comprehensive image of the studied material. The co-doped samples exhibit extremely low resistivity, close to $1\times10^{-3}$ Ωcm – outperforming commonly used aluminum doped zinc oxide (AZO). We assume that the enhancement in carrier concentration after hafnium addition originates from the passivation of the deep oxygen vacancies, that act as electron trapping states along with decreasing the grain boundaries. Besides enhancing electronic properties, the co-doping opens a new possibilities of tuning both optical band gap and electrical properties. The proposed co-doped zinc oxide can found applications in the future electronic devices utilizing TCO materials such as flat panels, solar cells and variety of sensors.

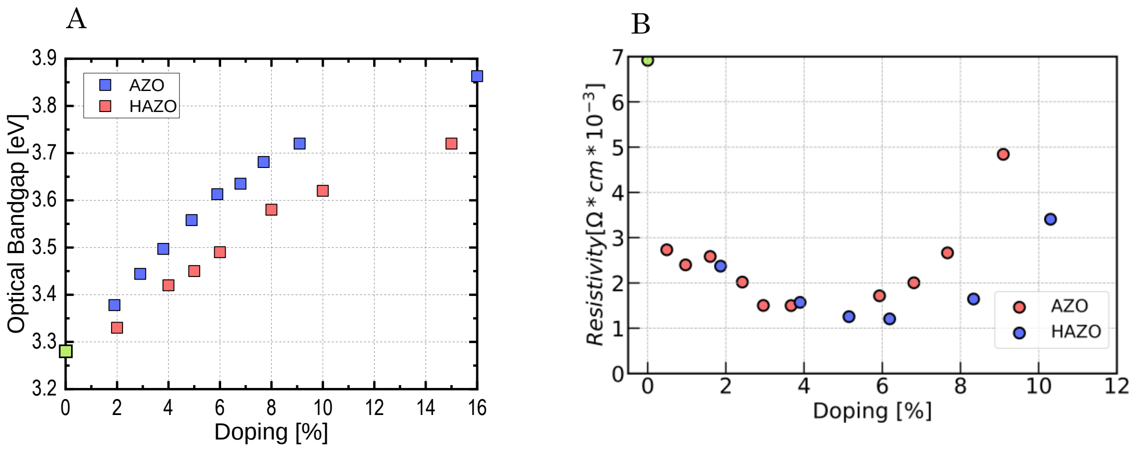


Figure 1. A) Optical bandgap widening with doping steadily increases, mainly due to Bernstein-Moss effect. B) Resistivity for differently doped samples shows a minimum around 4% and 6% for AZO and HAZO respectively.