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Ga-doping of nonpolar *m*-plane ZnMgO with high Mg contents

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The electrical and optical properties of *m*-plane Ga-doped ZnMgO alloys are analyzed by capacitance-voltage profiling, Hall effect, and IR reflectance and UV-VIS absorption spectroscopies, spanning more than four orders of magnitude in carrier concentration. Mg contents up to 50 % are achieved while maintaining the wurtzite phase, with a measured band-edge energy of 4.41 eV. Despite the deterioration of the electrical properties with Mg incorporation, high electron concentrations ($\sim 4.4 \times 10^{19}\ cm^{-3}$) are measured for Mg contents up to 35 %, revealing doping efficiencies close to 100 %. The potential physical origin for the drop of the electron concentration and mobility with Mg is analyzed and correlated to the absorption measurements. In ZnO:Ga epilayers band filling is observed, although upon alloying with Mg, bandgap shrinkage and Urbach tailing become evident. It is deduced that the observed carrier compensation arises from the presence of acceptor traps, such as V_{Zn} and V_{Zn}-Ga_{Zn} complexes, whereas impurity scattering and electron trapping at extended defects are the mechanisms affecting the mobility.

Keywords: *oxide, electrical transport, optical properties, phonons, impurities in semiconductors*

1. Introduction

The ZnO material system has started to play a central role in the development of transparent conductive oxides (TCOs) [1], where a high transparency and conductivity is desired. The wide bandgap of ZnO, 3.37 eV at 300 K, together with the very high electron concentrations that can be achieved (as high as $1 \times 10^{21}\ cm^{-3}$ [2]), offer a unique canvas for the development of novel TCOs. While for TCOs polycrystalline material may be acceptable, epitaxial ZnO is needed for devices that require a high control over the heterointerface with an alloy that serves as the barrier, such as high electron mobility transistors (HEMTs) [3,4], and intersubband-based devices [5,6], including quantum well infrared photodetectors and quantum cascade lasers. All of these devices have two important characteristics in common. First, they are unipolar, and therefore the lack of reliable p-type doping in ZnO [7] is not a drawback. Second, they require a heterojunction, i.e., the integration of a wider bandgap material, like ZnMgO, over ZnO. The control of the band offset at the heterointerface can thus be realized varying the Mg content, whereas in cases like the HEMT, the two-dimensional electron gas (2DEG) density at the interface can be controlled through the doping in the ZnMgO barrier, provided there are no internal electric fields or their effect is negligible. This is the case of the *m*-plane ZnMgO films analyzed in this study, where the *c*-axis is found in the plane of the heterointerface and so is the internal electric field typically present in this wurtzite crystal structure, avoiding the presence of polarization charge or the Quantum Confined Startk effect [8]. Therefore, achieving a high control of Mg incorporation and doping efficiency in non-polar epitaxial ZnMgO alloys seems a natural path for the development of the aforementioned devices.