Electrical Properties of ZnO Thin Films

Introduction

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ZnO is a multifunctional material that is used as polycrystalline material industrially as transparent conductive oxide (TCO). Also, the piezoelectric properties of crystalline material are employed in surface acoustic wave devices.

Here, we focus on electric properties of crystalline ZnO thin films grown by pulsed laser deposition on sapphire. Our studies have the aim to control donor-like defects and eventually achieve p-type conductivity [1]. This will open tremendous possibilities towards the development of UV and blue LEDs and lasers. These could pose a commercial alternative to GaN. ZnO has several (so far potential) advantages such as wet chemical processing and strong radiation hardness. We note that the electron mobility in thin films is limited by grain boundaries while in bulk material LO phonon scattering is the intrinsic limit *(Fig. 1)*.

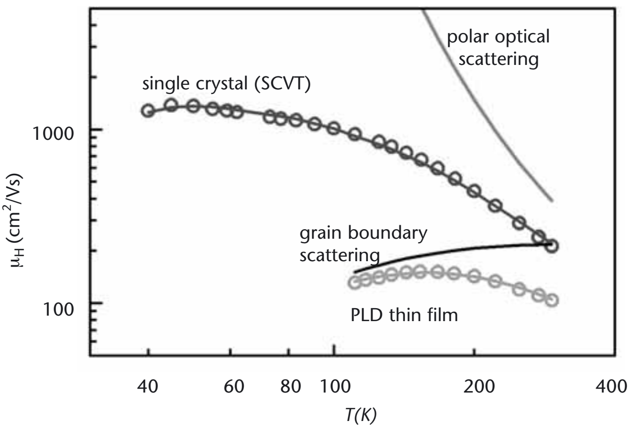

Figure 1
Temperature dependence of the mobility of electrons in ZnO bulk (EP) and a PLD thin film (circles: experimental data, solid lines through data: fits). Theoretical mobilities due to polar optical scattering and grain boundary scattering are shown as solid lines, other scattering mechanisms are omitted for clarity.

Shallow donors

Prerequisite for p-type conductivity is a sufficiently small concentration of donors that need to be compensated. Donors are separated into shallow and deep donors. The shallow donors have ionizations energies not larger than about 60 meV and are effective-mass like. For several elements such as hydrogen, In, Ga, and Al a microscopic identification was recently achieved [2] from a combination of Hall effect and donor-bound luminescence. We note that the deep donors are labeled E1, E2, ... and are not microscopically identified yet.

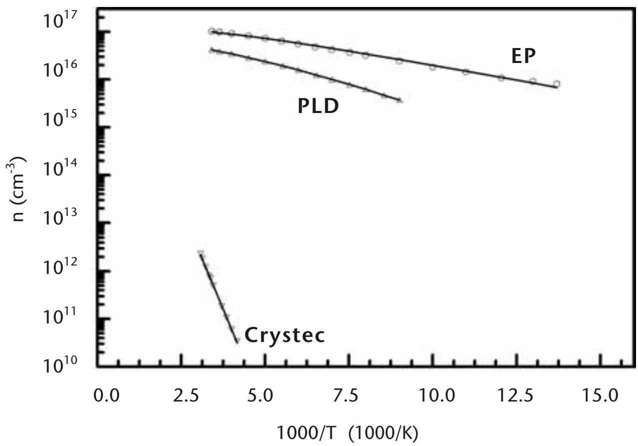

Figure 2
Free electron concentration of bulk ZnO (EP), PLD thin film and highly compensated bulk ZnO (Crystec) (symbols: experimental data, solid lines: fits)

In *Fig. 2* the temperature dependence of the electron concentration of a typical ZnO thin film is shown. Also a n-type bulk material (Eagle-Picher, EP) is shown. While the sample EP exhibits two shallow donors *(Tab. 1)*, the ZnO thin films exhibits only one, namely Al. The Al diffuses during growth from the sapphire substrate, a process that can be suppressed by a thin MgO buffer layer leading to semi-insulating ZnO thin films. The electrical activity of shallow donors was also compensated by us using nitrogen (co-)doping.

Table 1

Donor ionization energy and concentration obtained from Hall data (Fig. 2) for ZnO bulk (EP), PLD thin film and highly compensated bulk ZnO (Crystec).: This value corresponds to the concentration of the deep donor plus all shallow donors.*

Sample	E_{d1} (meV)	N_{d1} (10^{17} cm^{-3})	E_{d2} (meV)	N_{d2} (10^{17} cm^{-3})	NA (10^{15} cm^{-3})
EP	34	0.98	67	0.7	3
PLD	65	0.6	-	-	1.5
Crystec	299	1.9*	-	-	1

Deep donors

The third sample in the Hall data of Fig. 2 (Crystec) was fabricated using hydrothermal growth and is highly compensated with group-I elements. The apparent donor ionization energy is about 300 meV which is known as the E3 level. Deep donors are mainly studied with DLTS and thermal admittance spectroscopy (TAS) using Schottky diodes. Several levels are found in sample EP while only two deep levels are present in the PLD thin films (Tab. 2) [3]. We note that the E3 level found in the Hall data of the Crystec sample also shows up in the capacitance measurements on the other two samples, EP and PLD.

Table 2

Energetic position, concentration and capture cross section of deep donors in ZnO bulk (EP) and a ZnO PLD thin film

defect	E_c-E_t (meV)	σ (cm^2)	bulk (EP) N_t (cm^{-3})	PLD thin film N_t (cm^{-3})
E1	110 ± 20	1×10^{-13}	1.4×10^{15}	1.4×10^{15}
E3	300 ± 30	6×10^{-16}	2×10^{14}	6×10^{15}
E4	540 ± 40	1×10^{-13}	2×10^{14}	-
E5	840 ± 50		4×10^{14}	-

Summary

Great progress has been made in the control and understanding of n-type doping and conductivity of ZnO bulk crystals and ZnO thin films. The energy positions and the concentrations of shallow and deep donors have been identified. This is the basis to explore p-type conductivity.

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Literature

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[3] H. v. Wenkstern, M. Grundmann et al., Adv. Sol. State Physics (2005), in press.