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## DOPING OF THE WIDE-GAP SEMICONDUCTOR $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$ DURING MOLECULAR BEAM EPITAXY\*

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We investigated the *n*-type doping of the wide-gap II-VI semiconductor (CdMg)Te. The *n*-type doping of (CdMg)Te has previously been achieved in only a small range of magnesium concentration. By the use of zinc iodine as dopant source material, we obtained highly doped (CdMg)Te layers up to a magnesium concentration of 40%. The limiting factor for the free carrier concentration at room temperature is the occurrence of a deep level, which dominates the electrical properties at room temperature of layers with more than 30% magnesium. Compensating defects or defect complexes are considered, to explain the observed properties of the deep level, which do not seem to be characteristic of an isolated donor state.

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### 1. Introduction

The ternary wide-gap semiconductor (CdMg)Te seems to be a promising candidate for optoelectronic devices for the whole visible range of light [1]. (CdMg)Te has been found to be suitable for optoelectronics, already demonstrated in 1967 by the fabrication of an electroluminescent diode [2], but the crystal growth and the purity of the base materials turned out to be critical [3]. By the use of molecular beam epitaxy (MBE) (CdMg)Te has recently been produced as high quality thin films on (CdZn)Te substrates [1]. The lattice mismatch between CdTe and zinc blende MgTe has been found to be as low as 1% at room temperature. Considering the MgTe band gap of about 3.3 eV at 2 K [4, 5], (CdMg)Te is an ideal counterpart to the semimagnetic (CdMn)Te. Optical investigations on CdTe/(CdMg)Te and (CdMn)Te/(CdMg)Te structures reveal interesting properties of those structures [6, 7].

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Taking into account that optically pumped heterostructures with the base material (CdMg)Te have already been realized showing laser emission at room temperature [8], the doping of the wide-gap material (CdMg)Te might be a next step towards the application in optoelectronic devices. In this contribution we present results on the  $n$ -type doping of (CdMg)Te during molecular beam epitaxy.

## 2. Experimental details

$\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  layers were grown in a Riber 2300 MBE system on highly compensated CdTe and (CdZn)Te substrates. Details of the substrate preparation and sample growth process can be found elsewhere [9]. The absolute magnesium concentration was determined via the lattice constant derived from X-ray diffraction [4]. We examined the halogens Cl, Br and I as dopants, integrated into the MBE process in the form of zinc-halogenides. The electrical properties of non-degenerately doped layers were investigated, making use of van der Pauw measurements. The data were evaluated in the frame of Drude's model. For electrical measurements we used four small indium contacts in a van der Pauw configuration, attached by a thermobonder to the edges of the sample. The results of temperature dependent van der Pauw measurements were analyzed by applying the exact Fermi statistic  $n \approx N_C \frac{2}{\sqrt{\pi}} F_{1/2}(E_F - E_C)/kT$  ( $F_{1/2}$  is the Fermi integral). The activation energy of a dominating energy level was obtained by the respective numerical fit.

## 3. Results and discussion

Figure 1 shows the result of the iodine doping of  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  in comparison with the results of chlorine and bromine doping. The samples were produced under comparable growth conditions. The doping of (CdMg)Te with iodine is apparently more efficient at high magnesium concentrations than the use of chlorine or bromine.  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  can be degenerately doped with iodine up to a magnesium content of 30%. Above 30% the maximum free carrier concentration at room temperature decreases with increasing  $x$ -value, as it is observed for bromine and chlorine doped  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  at small concentrations of the ternary component [10]. At 40% Mg a free carrier concentration of  $1 \times 10^{17} \text{ cm}^{-3}$  at room temperature can be obtained under the growth conditions applied.

Evaluating the temperature dependence of the free carrier concentration  $n(T)$  in  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}:\text{I}$  layers (Fig. 2a), the reason for the drop of  $n$  at 300 K above 30% magnesium is evident. A deep level is dominating the electrical properties, giving rise to a strong temperature dependence of the free carrier density. The activation energy of this deep level was determined for nondegenerately doped layers. Table gives a summary of the dominating energy levels in  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}:\text{I}$ . Below 30% Mg, there is no dominating deep level. A deep level can be detected about 200 meV deep with respect to the conduction band minimum for magnesium contents exceeding 30%. For higher magnesium content, the activation energy rises only slightly with increasing magnesium concentration. A deep level was determined in Cl- and Br-doped  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  layers, too, which is the limiting factor for efficient  $n$ -type doping using these dopants [10]. The problem of deep levels in

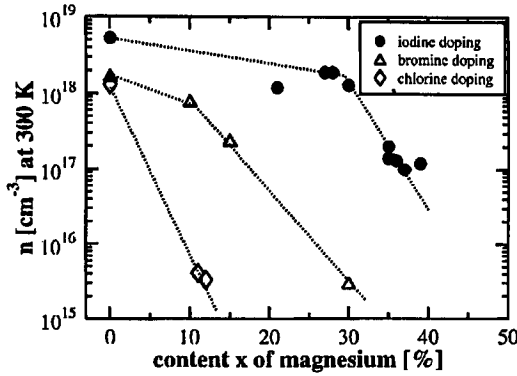


Fig. 1. Free carrier concentration at room temperature in halogen doped  $Cd_{1-x}Mg_xTe$  layers. With increasing concentration of the ternary component, the free carrier density decreases. In iodine doped layers, this effect is observed only above 30% magnesium. The dotted line should be a guide for the eye.

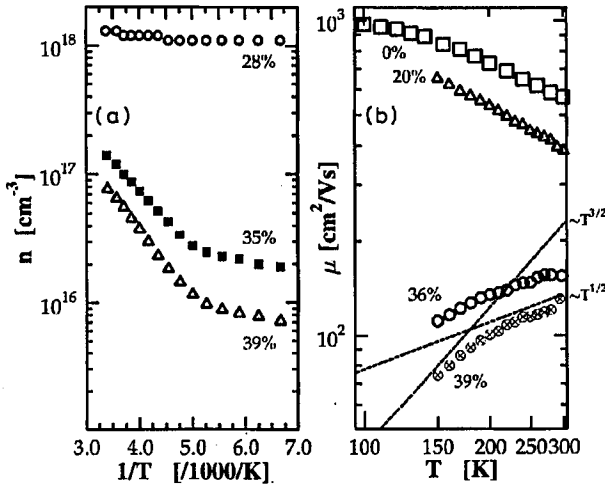


Fig. 2. (a) Free carrier density as function of temperature in iodine doped  $Cd_{1-x}Mg_xTe$  layers. Above  $x = 30\%$  a deep level dominates the electrical properties. (b) Free carrier mobility as a function of temperature. In layers with more than 30% magnesium, the mobility decreases proportionally with  $T^{3/2}$  at low temperatures, indicating that the limiting scattering mechanism might be due to ionized centers. For comparison, the dependence  $\mu \sim T^{1/2}$  is added, which indicates scattering due to optical phonons.

$(CdMg)Te:Cl$  has also been observed in bulk crystals of this material [11]. There, the deep level was ascribed to the existence of double acceptors, which should explain the phenomena of persistent photoconductivity [12].

TABLE

Thermal activation energy of electronic levels in iodine doped  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  layers. Above 30% Mg a deep level ( $E_T$ ) is dominating at room temperature, at low temperatures a shallow donor state ( $E_D$ ) can also be detected.

$x$ [%]	$E_T$ [meV]	$E_D$ [meV]
12	–	$7\pm 3$
20	–	$14\pm 5$
29	–	$25\pm 3$
35	$200\pm 10$	$15\pm 5$
36	$205\pm 10$	$10\pm 5$
39	$220\pm 10$	$10\pm 5$

A characteristic of the deep level in iodine doped  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  might be revealed from the temperature dependence of the free carrier mobility (Hall mobility) shown in Fig. 2b. The limiting scattering mechanism in layers with more than 30% magnesium could be attributed to the existence of ionized centres, according to the temperature dependence  $\mu \sim T^{3/2}$ . This property of the deep level could not be explained by the characteristic of an isolated donor, as it is proposed by Iseler et al. [13]. Therefore, we propose a compensation mechanism involving shallow donors ( $I_{\text{Te}}$ ) and compensating, acceptor-like deep levels with an activation energy of about 200 meV with respect to the conduction band. The microscopic origin of the deep level is not known, yet. Its generation seems to be dependent on the kind of donor species (I, Br, Cl) and the magnesium concentration (or the band gap). Thus, we propose that this might be a complex between donor atoms and an intrinsic defect (e.g.  $V_{\text{Te}}$ ) with a generation energy, which is dependent on the kind of donor atom. Further work has to be done to clarify the origin of the deep level, which is the limiting factor for the  $n$ -type doping of  $(\text{CdMg})\text{Te}$  above 30% Mg. In the case of a participating intrinsic defect, it seems to be possible to optimize the doping procedure by changing the MBE growth conditions.

#### 4. Conclusion

In conclusion, we have examined the  $n$ -type doping of  $\text{Cd}_{1-x}\text{Mg}_x\text{Te}$  with zinc-halogenides (Cl, Br and I). The iodine doping turns out to be most efficient up to a magnesium concentration of about 40%. The limiting factor for the free carrier concentration at room temperature is shown to be the occurrence of a deep level, which dominates the electrical properties of layers above 30% magnesium. The origin of this deep level might be discussed in the frame of a compensation mechanism between shallow donors and acceptor-like intrinsic defect complexes, 200 meV deep with respect to the conduction band minimum.

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