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Citation: [AIP Conference Proceedings](#) **1199**, 29 (2010); doi: 10.1063/1.3295420

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Study of PbTe *p*-Type Doping With BaF₂

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Abstract. We investigate here the electrical and structural properties of PbTe layers doped with BaF₂. The layers were grown on (111) BaF₂ substrates by molecular beam epitaxy. The nominal doping level, defined as the beam flux ratio between BaF₂ and PbTe, was varied from 0.02 to 1%. The hole concentration increases monotonously from 5×10^{17} to 1×10^{19} cm⁻³ as the doping level is raised from 0.02 to 0.4%, and saturates at $p \sim 10^{19}$ cm⁻³ for higher doping levels. This result demonstrates that PbTe can be effectively *p*-type doped with BaF₂. Even for the highest doping levels, the PbTe layers remained with a good structural quality, as evidenced by the (222) x-ray rocking curves.

Keywords: lead telluride; barium fluoride; molecular beam epitaxy; *p*-type doping; electrical properties.

PACS: 81.05.Hd; 81.15.Hi; 73.61.-r; 68.37.Hk.

INTRODUCTION

Lead telluride is a narrow gap semiconductor that finds its applications in thermoelectric devices [1,2] and in infrared lasers and detectors [3]. *n*-Type doping of the narrow gap semiconductor PbTe is obtained in a controlled manner up to 10^{20} cm⁻³ using Bi₂Te₃ as a dopant [4]. Contrarily, the *p*-type doping of PbTe at high levels is not easily achieved. For device applications, the control of PbTe *p*-type doping is highly desirable.

In this work, we present results on the investigation of electrical and structural properties of PbTe epitaxial layers doped with BaF₂. For this purpose, PbTe:BaF₂ epilayers were grown by molecular beam epitaxy on (111) BaF₂ substrates. In order to control the doping level, the flux ratio between BaF₂ and PbTe was ranged from 0.02 to 1%. The electrical properties were determined by Hall effect and resistivity measurements at room and liquid nitrogen temperatures. X-ray rocking curves around the (222) Bragg peak was measured to evaluate the structural characteristics.

RESULTS AND DISCUSSION

The PbTe layers were grown on freshly cleaved (111) BaF₂ substrates by molecular beam epitaxy (MBE) in a Riber 32P MBE system equipped with effusion cells containing PbTe, Te and BaF₂. The beam equivalent pressure (BEP) of each cell was measured separately in an ion-gauge flux monitor. During this experiment, the PbTe cell temperature was

kept at 645 °C, leading to a BEP of 5.8×10^{-7} Torr. The layers were deposited at a substrate temperature of 300 °C. In these conditions, the growth rate was 1.1 μm/h.

To determine the electrical properties, Van der Pauw geometry samples were prepared by soldering Au wires with In pellets. Resistivity and Hall effect measurements were performed at 300 and 77 K with a magnetic field of 0.7 Tesla.

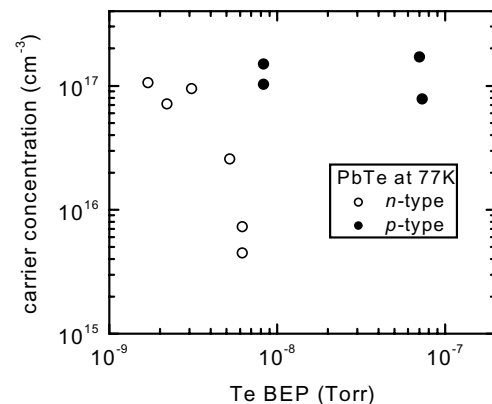


FIGURE 1. Carrier concentration at 77 K of PbTe layers grown by MBE with increasing Te beam equivalent pressure. The transition from *n* to *p*-type occurs at a Te flux of 8×10^{-9} Torr.

The electrical characteristics of undoped lead salts are controlled by native defects created by the deviation from stoichiometry, i.e. metal or chalcogen vacancies act as acceptors or donors, respectively.

Before growing the BaF₂ doped PbTe sample series, we first determined the additional Te flux necessary to obtain a *p*-type PbTe layer controlled only by Pb vacancies. Figure 1 shows the carrier concentration at 77 K of PbTe layers grown at different Te fluxes. For this purpose, the Te cell temperature was increased from 259 to 295 °C. In these conditions, the transition from *n* to *p*-type occurred with an additional Te flux of 8.2x10⁻⁹ Torr. The sample with this additional Te flux, which exhibited a hole concentration of 1x10¹⁷ cm⁻³, was set as the reference to start doping with BaF₂.

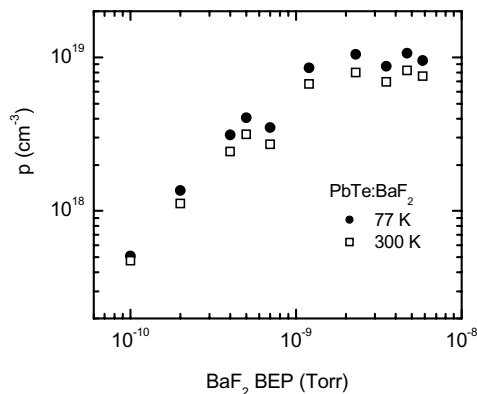


FIGURE 2. Hole concentration of PbTe layers as a function of BaF₂ beam flux. *p*-Type layers with concentration up to 10¹⁹ cm⁻³ were obtained.

To obtain the PbTe layers with different BaF₂ doping levels, a series of samples were produced with BaF₂ effusion cell temperature varying from 850 to 1040 °C, which gave a BaF₂ beam equivalent pressure ranging from 1.0x10⁻¹⁰ to 5.8x10⁻⁹ Torr. Consequently, the nominal doping level, defined as the BEP ratio between BaF₂ and PbTe, varied from 0.02 to 1%.

Figure 2 shows the hole concentration at 77 and 300 K of the PbTe layers doped with BaF₂. It increases from 5x10¹⁷ to 1x10¹⁹ cm⁻³ as the BaF₂ beam flux raises from 1x10⁻¹⁰ to 2x10⁻⁹ Torr (doping levels from 0.02 to 0.4%), and saturates at *p* ~ 10¹⁹ cm⁻³ for higher doping levels. This result evidences that PbTe can be effectively *p*-type doped with BaF₂ up to 10¹⁹ cm⁻³, and that the doping can be controlled by varying the BaF₂ beam flux in a specific range.

The difference between the carrier concentration at room and liquid nitrogen temperatures is small, as can be seen in Figure 2. This fact indicates that no thermal activation is present in the whole doping range investigated. The result observed here suggests that the impurity levels in the PbTe doped with BaF₂ remain resonant with the valence band.

The Hall mobility at 77 and 300 K of the PbTe:BaF₂ layers is shown in Figure 3 as a function of the BaF₂ beam equivalent pressure. The mobility at

300 K has only a small decrease from 500 to 400 cm²/V.s, as the doping level is increased. This is an expected behavior, since phonons dominate over other scattering mechanisms at room temperature. In the other hand, at 77 K, it decreases from 10000 to 2000 cm²/V.s as the doping level increases from 0.02 to 1%, indicating that additional carrier scattering process start to limit the mobility at this intermediate temperature as the hole concentration increases.

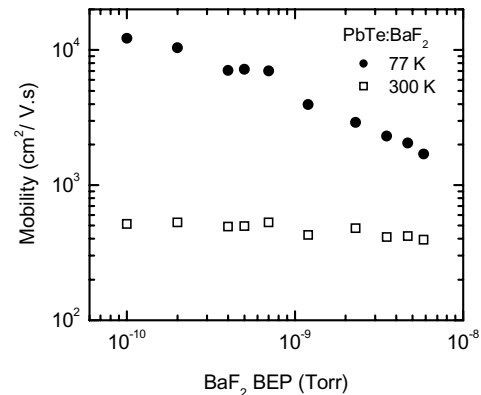


FIGURE 3. Mobility at 77 and 300 K of PbTe layers doped with BaF₂ as a function of BaF₂ beam equivalent pressure.

To determine the structural characteristics of the doped layers, the x-ray rocking curves were measured around the (222) PbTe Bragg peaks in a Philips X'Pert high resolution diffractometer. The full width at half maximum of the PbTe rocking curves varied from 120 to 330" as the BaF₂ doping level is raised. It indicates that PbTe layers remain with a relatively good crystalline quality even for the highest doping level produced here. This fact shows that the pronounced reduction of the mobility at 77 K is mainly due to the substantial increase of the hole concentration.

ACKNOWLEDGMENTS

This work is supported by CNPq and FAPESP funding agencies. U.A. Mengui acknowledges the CNPq Ph.D. scholarship.

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