Characterization of PbTe $p-n^+$ Junction Grown by Molecular Beam Epitaxy

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In this work we investigate the electrical properties of PbTe $p-n^+$ junction. Mesa diodes were fabricated from $p-n^+$ PbTe layers grown on (111) BaF_2 substrates by molecular beam epitaxy. From the analysis of the current versus voltage characteristic measured at 80K, the incremental differential resistance and the series resistance were determined. The capacitance versus voltage curves were measured at a frequency of 1MHz. The one-sided abrupt junction was checked through the $1/C^2$xV plot. From the linear fit, the hole concentration and the depletion layer width in the p-side were obtained. The high detectivity values measured for the $p-n^+$ PbTe diode confirm that it is very suitable for infrared detection.

1 Introduction

The lead salts are appropriate materials for infrared detection applications [1]. Due to its cutoff wavelength λ_c=5.9 μm at 77K, PbTe is an interesting option for the mid-wavelength infrared region. PbTe one-sided abrupt $p-n^+$ junctions have been proved to work properly as infrared sensors [2-4]. The detector performance strongly depends on the electrical characteristics of this junction.

In this work, we investigate the electrical characteristics of mesa diodes fabricated from $p-n^+$ PbTe layers grown by molecular beam epitaxy on (111) BaF_2 substrates. For this purpose, dedicated current versus voltage (IxV) and capacitance versus voltage (CxV) measurement systems were employed, tested and calibrated with commercially available devices. Both systems were computer controlled through an IEEE-488 interface and we have developed the control and measure programs in Visual Basic platform.

2 Sample preparation

The samples were grown on freshly cleaved (111) BaF_2 substrates by molecular beam epitaxy in a RIBER 32P MBE apparatus equipped with PbTe, Te and Bi_2Te_3 effusion cells [5]. The beam equivalent pressure (BEP) originating from each effusion cell was measured separately in a Bayer-Alpert flux monitor, and was used as the main growth parameter. A 12 keV reflection high-energy electron diffraction (RHEED) system was used to evaluate *in situ* the growth conditions. During this experiment, the growth temperature was always 300^{o}C. Before growing the actual $p-n^+$ structures, reference epitaxial layers were grown on BaF_2 substrates and characterized by Hall effect measurements, in order to obtain the desired carrier concentration for each layer in the junction. The PbTe flux was about 7x10^{-7} Torr, leading to a growth rate of 2.2 Å/s. The p-type layer, with a hole concentration of approximately 1x10^{17} cm^{-3}, was obtained using an additional Te flux to the PbTe main beam in a ratio of 1:10. Keeping this PbTe flux but using an additional Te flux in ratio of 1:50, a series of Bi doped PbTe epitaxial layers were grown with Bi_2Te_3 effusion cell temperatures varying from 370 to 450^{o}C. In these conditions, the electron concentration at 77K varied from 1x10^{17} to 4x10^{19} cm^{-3}, as determined by Hall measurements. For all these layers, the growth started with an island nucleation, evidenced by a spotty RHEED pattern. After 0.5 to 1 min (600 to 1200Å), the initial islands coalesced and the RHEED pattern changed to a streaky one. As the layer thickness reached approximately 0.5 μm, the RHEED pattern already showed elongated spots lying on a semicircle, characteristic of an atomically flat surface. This RHEED pattern persisted until the end of growth, and no surface reconstruction was observed.

The $p-n^+$ junction sample was then formed by growing the first p-type PbTe layer (6 μm thick and $\sim$1x10^{17} holes/cm^3) followed by the 2 μm thick n^+ PbTe layer with electron concentration of 1x10^{19} cm^{-3}. In order to electrically characterize this junction, mesa structures, as shown in Fig. 1, were etched in the samples. Au discs with 200 nm of thickness, as monitored by a quartz crystal oscillator, were deposited on the n^+ layer from an electron beam source through a stainless steel mask with holes of 0.3 mm in diameter. These Au discs were used as protective masks for the etching as well as metallic contacts. The mesas were etched with a Br_2:HBr:H_2O (1:40:40) solution. Additional gold pads were deposited on the p-side. Gold wires were soldered to both Au pads with indium. The diode was mounted on a Cu plate and assembled in a LN_2 cryostat.

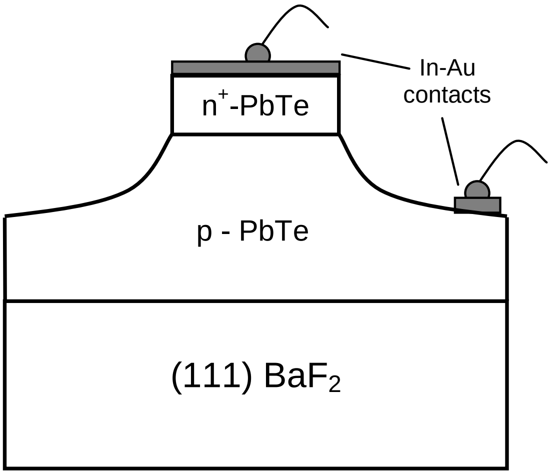

Figure 1. Schematic cross-section of the $p-n^+$ mesa diode fabricated from PbTe layers grown on BaF_2.

3 Electrical characterization

The resistivity, carrier concentration and mobility of the reference layers were measured at 300 and 77K in a automatic data acquisition Hall Effect system with an electromagnet field of 0.7 Tesla.

To measure the current versus voltage (IxV) characteristic of the diode, a dedicated system composed by a programmable power supply (Keithley 220), an ammeter (Keithley 2010) and a voltmeter (Keithley 199) was employed using a special cable assembly which guarantees accurate measurement of the exact voltage drop across the junction and of the actual current flow. The system is computer controlled through an IEEE-488 interface and we have developed the IxV control and measurement program in a Visual Basic platform. The IxV curves of commercial Si diodes were used to test and calibrate the system.

Figure 2 (upper panel) shows the IxV curve of the PbTe $p-n^+$ junction at 80K. This is a typical IxV curve for PbTe junctions, showing a leakage resistance in the reverse bias condition and a series resistance in the forward direction. The graph in the lower panel of Fig. 2 shows the inverse derivative of the IxV curve. A value of 950Ω for the incremental differential resistance at zero bias (R_0) was directly obtained from this plot, leading to a R_oA product of 2.3Ω.cm^2, which is approximately one order of magnitude lower than those found in the literature [2]. A relatively higher dislocation density in the PbTe layer may be responsible for this behavior. This fact is also in agreement to the relatively low saturation mobility (at low temperatures) in our p-type layer as compared to the values found in the literature. The IxV curve shown in Fig. 2 also indicates that the series resistance observed in our diode tends to a value of less than 100Ω.

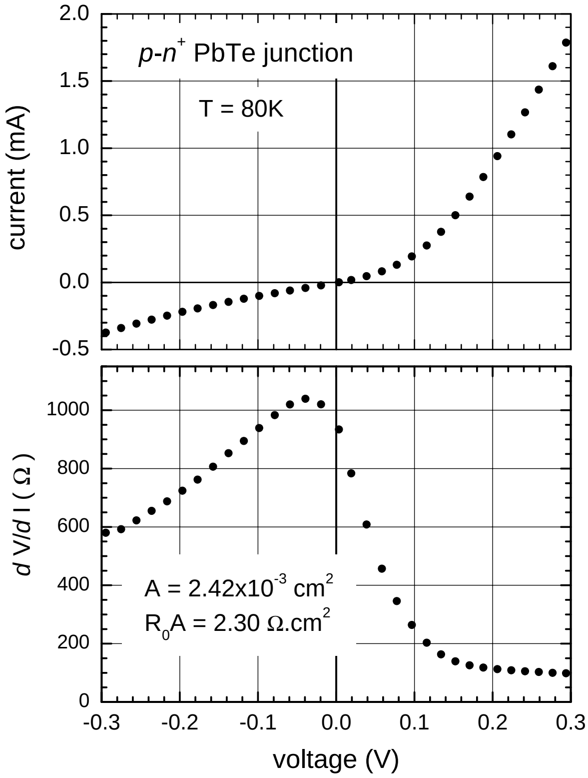

Figure 2. Current versus voltage curve (upper panel) for a $p-n^+$ PbTe diode grown on (111) BaF_2 substrate. The inverse of the derivative of the IxV curve is plotted in the lower panel.

To further characterize the $p-n^+$ diode, CxV curves were measured with a 1 MHz HP4280A capacitance meter. This equipment was also controlled via an IEEE-488 interface and a measurement program was developed in Visual Basic. A background capacitance which includes the cables and the cryostat with open contacts was measured as a function of applied voltage and was subtracted from each CxV measurement. Fig. 3 shows the 1/C^2 versus reverse voltage plot for our p-n^+ diode, where C is the capacitance per unit area. Its almost linear behavior indicates that a one-sided abrupt junction was formed.

For this type of junction, the slope of the 1/C^{2}xV plot is given by:

$$d(1/C^2)/dV = 2/(q\kappa\varepsilon_0 p),$$

where q is the electron charge, κ is the dielectric constant, ε_0 is the vacuum permittivity and p is the hole concentration. From the slope of the solid line in Fig. 3 and using $\kappa = 400$ for PbTe, a value of $p = 5\times10^{16}$cm^{-3} was obtained, which is close to that measured by Hall effect. The depletion width W can be also obtained by the CxV characteristic through

$$W(V) = \kappa\varepsilon_0/C(V).$$

For zero bias (V=0), the depletion width for our junction turned out to be 0.5 μm, increasing to 0.77 μm as the intensity of the reverse voltage rised to 0.40V.

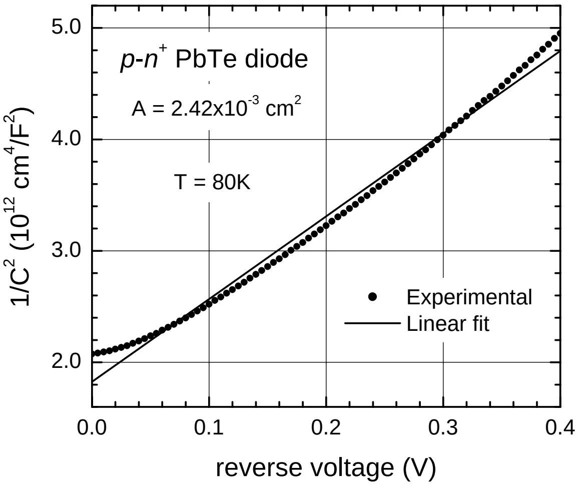

Figure 3. Capacitance versus voltage plot of a $p-n^+$PbTe junction grown on (111)BaF$_2$ substrate. The solid line is a least-squares linear fit to the data.

In order to test the fabricated device as an infrared detector, the integral detectivity D* of the p-n^+ diode was measured at 80K (FOV=90^o). A blackbody source (T=900K) illuminated the detector through the BaF$_2$ side with a power density of 565 μW/cm^2 through a chopper with frequency of 900Hz. The signal to noise ratio measured in a lock in amplifier with a bandwidth of 14 Hz was 8400, leading to an integral detectivity D* of 1.1x10^9 cmHz$^{1/2}$W^{-1}. This value indicates that the p-n^+ PbTe diode is very suitable for infrared detection.

4 Conclusions

$p-n^+$ PbTe junctions grown by MBE on BaF$_2$ were electrically characterized. From the IxV curve, the R_oA product and the series resistance were determined. The 1/C^{2}xV plot suggested that a one-sided abrupt junction was formed. The hole concentration and the depletion layer width of the p-side were determined by linear fitting. Despite the relatively small R_oA product measured, the p-n^+ PbTe diodes exhibited high detectivity D* values, and confirmed to be very appropriate for infrared detection application.

Acknowledgement

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