Characterization of Al-doped ZnTe layer using scanning capacitance microscopy and Kelvin probe force microscopy

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Abstract. Al-doped ZnTe layer in ZnTe LED fabricated by Al thermal diffusion has been characterized using cross-sectional scanning capacitance microscopy (SCM) and Kelvin probe force microscopy (KFM), and the results were verified by comparing with the result of the electron beam induced current (EBIC) measurements. Both SCM and KFM images showed contrast changes between Al diffusion layer and p-type substrate, indicating the conductivity type conversion in ZnTe. The distance from the surface of ZnTe to the contrast change position was around 1.8 μm, in consistent with the result of EBIC measurement. The surface potential of the Al diffusion layer was found to be almost constant, implying that the diffusion layer is relatively homogenous in depth direction. Thus, SCM and KFM are capable of providing the electrical information on ZnTe LED.

1. Introduction
ZnTe is expected as a promising material for a variety of optoelectronic devices such as pure green light emitting devices because of its direct transition band gap of 2.26 eV at room temperature. ZnTe can be doped in p-type easily, but the growth of n-type material was difficult due to the so-called self-compensation effect and the incorporation of residual impurities. Several efforts have been made to grow n-type ZnTe by low temperature epitaxial growth techniques such as metalorganic vapor phase epitaxy (MOVPE) [1,2] and molecular beam epitaxy (MBE) [3,4]. The n-type ZnTe layer with high conductivity has been successfully achieved by using ZnTe substrates instead of GaAs ones [1,4]. The thermal diffusion of Al is also promising technique in obtaining n-type ZnTe. Recently, pn-junction light emitting diodes (LEDs) have been fabricated by the diffusion technique using high-quality bulk crystals grown by a vertical gradient freezing method [5]. We have also fabricated a ZnTe LED by Al diffusion using Bridgman-grown substrates, and observed the pure-green electroluminescence at room temperature [6, 7]. The Al diffused layers were characterized using the depth dependence of photoluminescence spectroscopy, and the origin and the distribution of the defects has been clarified [8]. In order to fabricate ZnTe LEDs with better performance, it is essential to know the depth dependence of the electrical properties in the Al diffusion layer. However, to our knowledge, there is no paper dealing with such electrical properties of the Al-diffused layer in ZnTe.

Recently, scanning probe microscopy (SPM) has been used to characterize not only the surface morphology of different materials, but also variations of the spatial doping level and the surface
potential with respect to the vacuum level of the probe [9-11]. These techniques are most valuable in allowing the local variations of electrical properties to be mapped in the nanometer scale. Among the several techniques of the SPM, scanning capacitance microscopy (SCM) has proved to be a powerful tool for 2D profiling of conductivity type and carrier concentration gradients [9]. Kelvin probe force microscopy (KFM) is also promising for the mapping of the work functions of materials, which depend on dopant type and concentration in the case of semiconductor [10,11]. Several reports have demonstrated the potential of these techniques for characterising Si and III-V devices [9,12,13]. However, these techniques have never used to investigate ZnTe related materials or devices.

In this study, we have attempted to characterize the electrical properties of Al diffusion layers using SCM and KFM, and the results were verified with the results of electron beam induced current (EBIC) measurements.

2. Experiments
The sample used in this work was a ZnTe p-n homojunction structure fabricated by Al thermal diffusion technique as reported previously [6,7]. Briefly, p-type ZnTe was used as substrates, and they were cleaned ultrasonically in the organic solvents. Al thin film was deposited on the p-type ZnTe substrate as a diffusion source. The thermal diffusion was carried out in the electrical furnace in N₂ atmosphere. After the thermal diffusion, an electroless Pd was deposited on the back surface in order to fabricate the LED structure.

The I-V characteristic of ZnTe LED was recorded at room temperature. In order to evaluate the depth of pn-junction, the EBIC measurement was carried out in the secondary electron microscope (SEM).

All of the SPM measurements were made in air with a Multimode Scanning Probe Microscope from Digital Instruments / Veeco with a NanoScope III System Controller and a Quadrexed Electronics Module. For the SCM measurements, SPM was operated in contact mode AFM using a commercially available PtIr-coated cantilever, and the data was taken in so-called dC/dV data mode with a fixed ac modulation voltage frequency of 60 kHz applied to the SPM probe. For KFM measurements, a commercially available CoIr-coated cantilever was used, and topography was taken in tapping mode AFM, whereas surface potential was imaged using the lift mode. In the lift mode, a SPM probe applied an AC plus DC bias was scanned across the surface at a constant tip-sample separation. A lock-in technique is used to monitor the first harmonic of the oscillating amplitude of the cantilever as a function of the variation of the DC bias on the probe. When the oscillating amplitude nulls, the DC bias equals the local surface potential of the sample, and its value is recorded to form the surface potential image. Details have been described by other researchers [14,15]. The samples were cleaved in air just prior to the measurement and mounted on a sample holder.

3. Results and discussion
Figure 1 shows the I-V characteristic of ZnTe LED fabricated in this experiment. Rectification behaviour of pn-junction was observed clearly with a turn-on voltage of about 3 V. The ZnTe LED showed a green electroluminescence under the forward bias, as shown in the inset of figure 1.

The depth of pn-junction was evaluated by the cross-sectional EBIC measurement of ZnTe LED. Figure 2 (a) shows a mixture image of the secondary electron and EBIC signal of the

![Fig. 1. I-V characteristic of ZnTe LED fabricated in this experiment. The inset is a picture of ZnTe LED under forward bias at room temperature.](image-url)
cross-section of ZnTe LED, and the EBIC signal is shown in figure 2 (b). The bright region in ZnTe in figure 2 (a) corresponds to the area where the strong EBIC signal is obtained. From the figure 2 (a), the depth of pn-junction is estimated to be about 1.8 μm.

Figure 3 (a) and (b) show the topography and KFM images of ZnTe LED. The reason why the height of surface Al film is higher than ZnTe is probably due to the fact that the surface Al film is expanded slightly when cleaving the ZnTe LED from the backside. This tendency was always observed when evaluating the cross-section of ZnTe LED. KFM image shows a light (n-side) to dark (p-side) transition corresponding to the built-in potential drop across the pn-junction. As can be seen from figure 3 (c), the surface potential in the Al diffusion layer is almost constant, implying that the diffusion layer is relatively homogenous in depth direction. The distance from the Al/ZnTe interface to the maximum position of the electric field is about 1.8 μm, consistent with the result of EBIC shown in figure 2. However, the potential difference between the n-side and p-side of the sample is about 0.25 eV, which is much lower than the expected built-in potential of about 2.2 eV. This disagreement could be explained in terms of band bending due to surface states. The position of $E_F$ for p-type ZnTe as-cleaved in vacuum was reported to ~0.4 eV above the valence band maximum [16]. Assuming the band bending of the p-type ZnTe is only 0.4 eV, a band bending higher than 1.55 eV is obtained for the n-type ZnTe.

Figure 4 (a) and (b) show the topography and SCM images of ZnTe LED. The contrast change was observed clearly in the SCM image, indicating the change in conductivity in ZnTe. In Al diffusion layer, $dC/dV$ signal is almost constant, indicating that the distribution of the carrier concentration in the diffusion layer is relatively homogenous along with the depth direction, in good agreement with the results of KFM measurements. The distance from the Al/ZnTe interface to the position where the
Fig. 4. Topography (a) and $dC/dV$ amplitude (b) images of ZnTe LED. (c) The data are plotted along the arrow in figure (a), for the topography (top), the $dC/dV$ amplitude (bottom).

contrast changes is about 1.8 $\mu$m, consistent with the result of EBIC.

As described above, the results of KFM and SCM measurements are consistent with those of EBIC. In addition, the information of the electrical properties in the depth direction can be obtained by using these techniques. Therefore, it is concluded that the KFM and SCM are potential techniques to characterize the ZnTe material and devices.

4. Summary
The Al-doped ZnTe layer in the ZnTe LED has been characterized by using KFM and SCM. Both images showed a clear contrast at the interface between $n$-type and $p$-type region. The Al diffusion layer was found to be relatively homogenous in depth direction. The obtained results were consistent with the result of the EBIC measurement. Thus, SCM and KFM are capable of providing the electrical information on the ZnTe LED.

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