Tellurium-doped $Al_{0.43}Ga_{0.57}As/(In_{0.2})GaAs$ modulation doped heterostructures by molecular-beam-epitaxy

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Te has previously been demonstrated to have a shallower deep donor (*DX*-center) level than Si in AlGaAs. In this work, Te-doped $Al_{0.43}Ga_{0.57}As/GaAs$ and pseudomorphic $Al_{0.43}Ga_{0.57}As/In_{0.2}Ga_{0.8}As$ modulation-doped heterostructures (MDHs) grown by MBE have been studied. The conduction band offset ΔE_c in the pseudomorphic AlGaAs/InGaAs material system has a maximum at 43% Al mole fraction. This allows maximum carrier confinement in the quantum well. Two-dimensional electron densities and mobilities $2.36\times10^{12}\ \mathrm{cm}^{-2}$ and $7794\ \mathrm{cm}^2/\mathrm{V\,s}$ at 300 K and $2.17\times10^{12}\ \mathrm{cm}^{-2}$ and $24\,379\ \mathrm{cm}^2/\mathrm{V\,s}$ at 77 K (in the dark) have been obtained in Te-doped pseudomorphic MDHs. *© 1995 American Institute of Physics.*

GaAs based pseudomorphic high electric mobility transistors (PHEMTs) with InGaAs single quantum wells have received considerable interest for various application in the microwave and millimeter-wave regimes. For high power applications, it is desirable to increase Al mole fraction in the $Al_xGa_{1-x}As$ barrier layer, since both the Schottky barrier height and the conduction band offset (ΔE_c) at the heterointerface increase with increasing Al mole fraction for x less than 0.43. This would give rise to a lower gate leakage current, a higher gate-to-drain breakdown voltage, and a larger full channel current density. However, the deep donor (*DX*-center) associated with Si, which has been widely used as the *n*-type dopant for GaAs based materials, has limited the maximum density of two-dimensional (2D) electron gas obtainable from the AlGaAs/InGaAs system when the Al mole fraction is larger than 30%.[1]

The *DX*-center concentration in AlGaAs layers can be reduced by doping with the group VI element Te, because the *DX*-center level in Te-doped AlGaAs layers is shallower than that in Si-doped layers.[2–5] In the past, Te doping has been used extensively in liquid-phase-epitaxy of GaAs-based materials.[6] Recently, there were several reports of Te-doped GaAs and AlGaAs grown by metalorganic chemical vapor deposition.[7] Te-doped GaAs grown by molecular beam epitaxy (MBE) has also been studied using PbTe[8,9] as a ‘‘captive source’’.[10] However, because of the substantial loss of Te at the temperature for growth of high quality GaAs and AlGaAs, Te has been used exclusively in MBE for those materials where group IV elements are predominately acceptorlike, such as GaSb and AlSb. Very recently, Se-doped AlGaAs/GaAs MDHs grown by MDE were reported.[11,12] However, the Al mole fraction in these Se-doped MDHs was chosen below 0.3 for stable low-temperature operation of devices. In this work, we report the results of Te-doped AlGaAs/GaAs and AlGaAs/InGaAs modulation doped structures. The Al mole fraction in these MDHs was chosen as 0.43 to maximize ΔE_c at the heterointerface, and therefore the 2D electron density in the channel.

The use of Te instead of Si as a dopant in MBE grown MDHs has several advantages. The diffusion coefficient of Te is much lower than that of Si,[13] which promises abrupt doping profiles. The operating temperature of the Te cell is 500–550 °C, which is much lower than that used for Si, which is usually above 1200 °C. Therefore, unintentional impurity incorporation can be greatly reduced. However, because Te has a much higher vapor pressure than Si, to prevent the evaporation of Te adatoms and obtain reproducible doping densities, Te-doped MDHs must be grown at a relatively lower temperature than the optimized growth temperature of AlGaAs. Fortunately, characteristics of MDHs are primarily determined by the quality of the channel, which can always be grown at optimized temperatures.

Epilayers were grown in a Varian GEN-II modular MBE system equipped with an arsenic valved cracker (EPI MBE products group, Saint Paul, MN). After desorbing the oxides at 640 °C, a 500 nm GaAs undoped buffer layer was grown on semi-insulating GaAs substrates, followed by a channel layer composed of 200 nm GaAs and 15 nm $In_{0.2}Ga_{0.8}As$ (for pseudomorphic structures), and an undoped $Al_{0.43}Ga_{0.57}As$ spacer layer. The growth was then interrupted and a Te planar doped layer was introduced with the arsenic shutter open. The MDHs were completed with a 30 nm undoped $Al_{0.43}Ga_{0.57}As$ barrier layer and a 5 nm undoped GaAs cap. Te was doped by surface-exchange doping using PbTe. A cracked arsenic source (As_2) was used in this study.

The substrate temperature (T_s) is very important in this work since Te adatoms tend to evaporate from the surface due to its high vapor pressure. T_s was 600 °C for the buffer layer, and ranged between 500 and 600 °C for the remaining layers. For AlGaAs/InGaAs pseudomorphic MDHs, T_s was 600 °C for the buffer layer, 550 °C for the channel and spacer, and 540 °C for the remaining layers. Subsequently, in this letter, unless specified, T_s will refer to the substrate temperature during Te deposition and the growth of subsequent layers. As_2 flux also had a great effect on the properties of Te-doped MDHs, such as 2D electron density (N_s) and mo-

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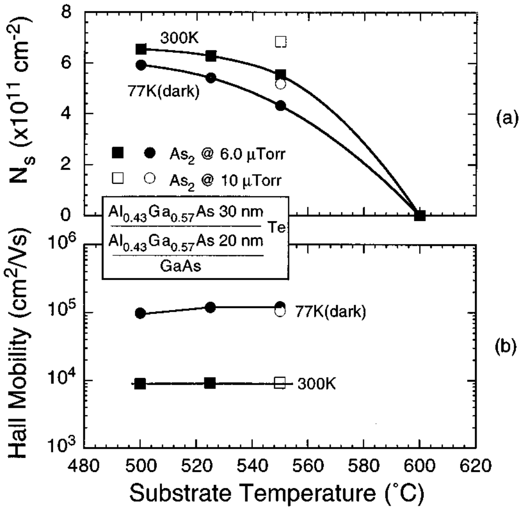

FIG. 1. (a) 2D Hall electron density and (b) mobility as functions of the substrate temperature during the deposition of Te and the growth of subsequent layers. The inset shows the structure of the Te-doped $Al_{0.43}Ga_{0.57}As$/GaAs MDHs.

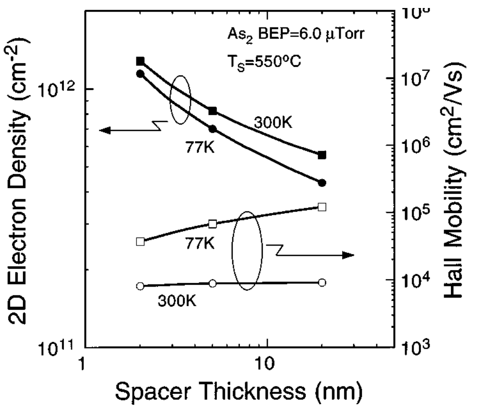

FIG. 2. 2D Hall electron density and mobility vs the thickness of the spacer of Te-doped $Al_{0.43}Ga_{0.57}As$/GaAs MDHs. The growth temperature during the Te deposition and the growth of subsequent layers is 550 °C and the As_2 BEP is 6.0×10^{-6} Torr.

bility (μ), as discussed below. The As_2 beam-equivalent pressure (BEP) was $6-8\times 10^{-6}$ Torr for the buffer, channel, and spacer, and $8-20\times 10^{-6}$ Torr for Te deposition and the growth of subsequent layers. Te-doped MDHs were characterized using Hall measurement. Samples were defined photolithographically and etched into cloverleaf patterns, and Ohmic contacts were formed by alloying indium dots at 450 °C under forming gas for 1 min.

Figure 1 presents the results of Hall measurements of five Te-doped $Al_{0.43}Ga_{0.57}As$/GaAs MDHs at both 300 and 77 K, showing the dependence of (a) 2D electron density and (b) Hall mobility on T_s. Detailed results are listed in Table I. These five samples have the same structure, as shown in the inset of the figure, and the same nominal Te density (the Te cell was set at the same temperature and the Te shutter was opened for the same period of time), but with different T_s. Samples A–D were grown under an As_2 BEP of 6×10^{-6} Torr (filled squares and circles), and sample E was grown under an As_2 BEP of 1×10^{-5} Torr (open square and circle). The low-temperature results were measured by cooling the samples from room temperature in the dark. Due to the evaporation of Te adatoms, 2D electron densities decrease with increasing T_s. Significant Te evaporation has been observed for $T_s>540$ °C. At 600 °C, the electron density was too small to be measured. Te evaporation can be greatly reduced by increasing the As_2 BEP during the deposition of Te as indicated in the figure. SIMS profiling indicated that there existed some Te segregation at 550 °C, but almost negligible at 500 °C. No Te accumulation at the surface was observed in any of the samples. Electron mobilities are about 9000 cm^2/V s at 300 K, and vary between 97 196 and 120 420 cm^2/V s at 77 K in the dark. These results are comparable with those obtained from Si-doped AlGaAs/GaAs MDHs with the same spacer thickness and similar electron densities.[14] A Si doped 30% AlGaAs/GaAs MDH (not optimized) grown in the same MBE system showed a mobility over 10^6 cm^2/V s at 11 K,[15] indicating negligible Te memory effect, at least in MBE systems.

TABLE I. 2D Hall electron densities and mobilities of Te-doped $Al_{0.43}Ga_{0.57}As$/GaAs MDHs which have the same structure and nominal Te doping density. The spacer is 200 Å.

Sample No.	T_s (°C)	As_2EBP (μ Torr)	N_S($\times 10^{11}$ cm^{-2}) 300 K	77 K	μ (cm^2/V s) 300 K	77 K
A	500	6.0	6.55	5.92	8876	97 196
B	525	6.0	6.28	5.42	9220	118 700
C	550	6.0	5.54	4.32	9137	120 420
D	600	6.0	⋯	⋯	⋯	⋯
E	550	10.0	6.85	5.18	9244	104 594

Shown in Fig. 2 are the 2D electron densities (N_s) and Hall mobilities (μ) of Te-doped $Al_{0.43}Ga_{0.57}As$/GaAs MDHs with different spacer thicknesses (L_s) and otherwise the same structure. N_s increases and μ decreases with decreasing L_s, as expected. At 2 nm spacer, N_s and μ are 1.28×10^{12} cm^{-2} and 8160 cm^2/V s at 300 K, 1.15×10^{12} cm^{-2} and 37 403 cm^2/V s at 77 K in the dark, and 1.39×10^{12} cm^{-2} and 41 753 cm^2/V s at 77 K after exposure to light, respectively. Good mobilities indicate very small Te back-diffusion into the channel.

The ΔE_c of AlGaAs/GaAs MDHs can be improved further by using a strained InGaAs single quantum well as the channel layer. In this study, a 15 nm InGaAs layer with 20% indium was used. Figure 3 presents the results for Te-doped $Al_{0.43}Ga_{0.57}As/In_{0.2}Ga_{0.8}As$ pseudomorphic MDHs that have the same structure as shown in the inset but with different Te doping densities. As a comparison, also shown in Fig. 3 are several results for previously reported Si-doped $Al_xGa_{1-x}As(x=0.15-0.35)/In_{0.2}Ga_{0.8}As$ MDHs with a similar spacer thickness.[16–19] Improvement of both electron density and mobility have been obtained from Te-doped $Al_{0.43}Ga_{0.57}As/In_{0.2}Ga_{0.8}As$ MDHs. This is believed to be due to better carrier confinement as the result of a larger ΔE_c. At 300 K, a 2D electron density of 2.36×10^{12} cm^{-2} with a mobility of 7794 cm^2/V s has been obtained in the pseudomorphic MDHs. The corresponding 77 K (in the dark) N_s and μ are 2.17×10^{12} cm^{-2} and 24 379 cm^2/V s, re-

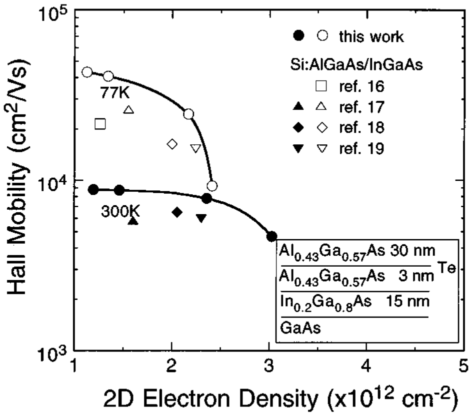

FIG. 3. 300 K (filled symbols) and 77 K (in the dark, open symbols) mobilities of pseudomorphic Te-doped $Al_{0.43}Ga_{0.57}As/In_{0.2}Ga_{0.8}As$ compared with Si-doped $AlGaAs/In_{0.2}Ga_{0.8}As$ MDHs as functions of the 2D electron density.

spectively. Further increase of Te density populates electrons into the AlGaAs barrier layer as indicated by the significant reduction in electron density at 77 K (in the dark) from its 300 K value and greatly reduced 77 K mobility.

In summary, Te-doped AlGaAs has been studied and applied to AlGaAs/GaAs and AlGaAs/InGaAs MDHs with 43% Al. As the result of shallower *DX* centers associated with Te and low diffusion coefficient of Te, high 2D electron density and high mobility were obtained from MDHs for both GaAs and InGaAs channels.

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