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Growth of InP high electron mobility transistor structures with Te doping

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Abstract

InP high electron mobility transistor (HEMT) structures with $In_{0.53}Ga_{0.47}As$ channels and $In_{0.52}Al_{0.48}As$ barriers were grown by molecular beam epitaxy. A GaTe source was used as an n-type dopant. Conventional structures with 50–100 Å InAlAs(Te) layers and Te-delta-doped structures were investigated. Both types of structures exhibited good transport characteristics, with mobilities of 8000–10,000 cm^2/V-s and sheet densities of 1–4 × 10^{12}/cm^2. Fluorination studies showed similar behavior for Si- and Te-doped HEMT structures, with donor deactivation resulting in substantial reductions in mobility and carrier density after exposure to fluorine.

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1. Introduction

InP high electron mobility transistors exhibit the highest speed characteristics of any kind of transistor, with cutoff frequencies over 500 GHz [1]. These structures were traditionally grown with InGaAs channels and InAlAs barriers on InP substrates. In recent years, advances in the growth of phosphide and antimonide layers, including alloys with mixed anions, have opened new possibilities for band-structure engineering to enhance device properties such as breakdown voltage and noise performance. The AlGaAsSb system, in particular, offers a broad range of conduction and valence band discontinuities to the InGaAlAs system for compositions lattice-matched to InP.

Silicon, the standard n-type dopant in arsenide and phosphide molecular beam epitaxy (MBE) systems, is an acceptor in GaSb, AlSb, and related

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alloys [2]. The preferred n-type dopant in many antimonide structures is Te, usually in the form of GaTe or PbTe sources [3]. In fact, many antimonide MBE systems do not have a Si source. Although Te has a diffusion coefficient that is reported to be two orders of magnitude lower than Si in GaAs [4], earlier work suggested that segregation and desorption of Te may make it unsuitable at the higher growth temperatures typically used for arsenides [5]. Studies have shown, however, that Te can be stable in GaAs and GaSb up to growth temperatures of 550 °C [6,7]. Pseudomorphic $In_{0.2}Ga_{0.8}As/Al_{0.4}Ga_{0.6}As$ high electron mobility transistor (HEMT) structures have been grown by MBE using Te doping in order to reduce the problem of the DX center associated with Si donors in AlGaAs [8]. Mobilities as high as $7800\,cm^2/V\text{-}s$ were achieved by using higher growth temperatures for the buffer and channel layers and then lowering the temperature to 500–540 °C for the Te delta doping. These heterostructures were fabricated into devices with good performance [9]. Te doping has also been used in metal-organic chemical vapor deposition to dope InGaAs/AlGaAs HEMTs [10] as well as quantum well lasers [11]. An additional motivation for studying Te doping in InP HEMTs is the Si deactivation problem. Several studies have established that Si dopants in InAlAs layers can be deactivated by fluorine during normal processing [12–16]. This is a serious problem in InP HEMT fabrication. Since Te is a dopant that sits in a group V site, as opposed to Si donors which occupy group III sites, there is the possibility that Te-doped InAlAs does not suffer from this problem. In summary, Te-doped InAlAs appears to offer advantages for InP HEMT applications. In this work, we have investigated this technology. Our work indeed demonstrates that Te doping is a viable option for this application.

2. Experimental procedures

The heterostructures were grown on semi-insulating InP (0 0 1) substrates by solid-source MBE, using a valved As cracker to produce As_2. We used stoichiometric Ga_1Te_1 (hereafter referred to as GaTe).[2] Typical heterostructures are shown in Fig. 1. The $In_xGa_{1-x}As$ channels and $In_yAl_{1-y}As$ barrier and buffer layers were nominally lattice-matched to InP. (X-ray diffraction measurements confirmed that $x = 0.53 \pm 0.03$ and $y = 0.52 \pm 0.03$.) The growth temperature was fixed at 450 °C, the V:III flux ratios were approximately 2:1, and the growth rate was 1.0 monolayers/s for all layers. The buffer layer and channel thicknesses were fixed at 3000 and 150 Å, respectively. Te delta-doping (Fig. 1b) was achieved by interrupting growth under As and opening the GaTe shutter for 10–100 s. Carrier densities and mobilities were measured on $5 \times 5\,mm^2$ samples by the Hall/Van der Pauw technique at a field of 0.37 T. The effects of fluorine were studied by dipping the samples in a buffered-oxide etch solution (7% HF, 34% NH_4F, 59% H_2O) and then annealing them at 450 °C for 120 s in N_2.

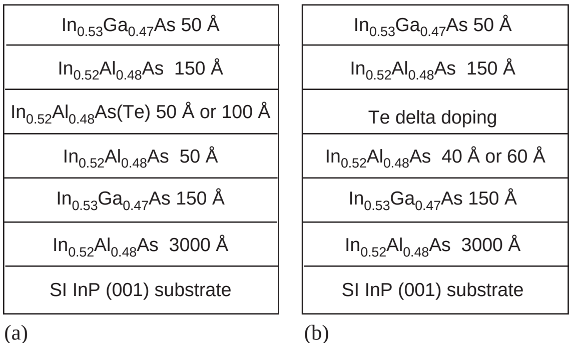

Fig. 1. Cross-sections for InP HEMT structures with (a) conventional Te doping and (b) Te delta doping.

3. Results and discussion

In Fig. 2, we show transport data for both conventional and delta-doped HEMT structures. The conventional structures have room-temperature mobilities of $9000–10{,}000\,cm^2/V\text{-}s$ with sheet densities of $1–2 \times 10^{12}/cm^2$. Mobilities as high as

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[2] Ga_2Te_3 has also been used as a source, but, as discussed by Furukawa and Mizuta, Ga_2Te_3, like Te, has a higher vapor pressure than GaTe and hence is less suitable for an MBE source [17].

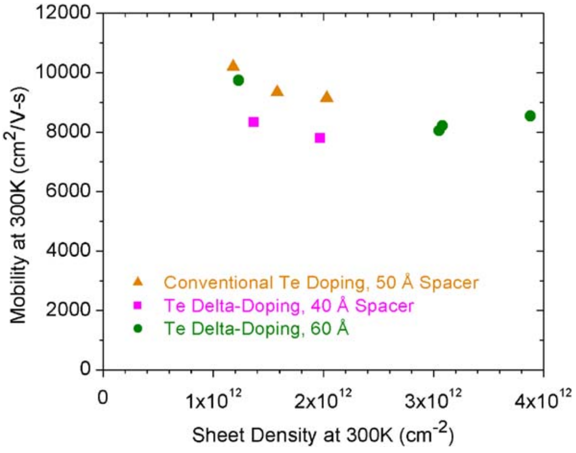

Fig. 2. Electron mobility and sheet carrier density for Te-doped InP HEMT structures.

$39{,}000\,\mathrm{cm^2/V\text{-}s}$ were measured at 77 K. The 300 K mobility of delta-doped structures with 40 Å spacer layers is degraded somewhat, with values near $8000\,\mathrm{cm^2/V\text{-}s}$. Increasing the spacer to 60 Å appears to improve the mobility of the delta-doped structures. An advantage of the delta-doping is that the gate-to-channel separation can be smaller, providing a better aspect ratio for sub-micron gate lengths. Our structures with 40 Å spacer layers have a gate-to-channel separation of only 190 Å which could be reduced further by decreasing the thickness of the 150 Å InAlAs layer. We note that these results were achieved without any attempts to optimize the growth temperature, growth rate, V:III ratio, or channel composition.

In Fig. 3, we show the variation of sheet carrier concentration with GaTe soak time for a series of delta-doped samples grown within a 4-day period. The sheet density appears to be well-behaved, allowing good control. (Note that self-consistent calculations show that a parallel channel will form in the upper InAlAs barrier for sheet densities above $4\times10^{12}/\mathrm{cm}^2$. Hence, the sample with $5.4\times10^{12}/\mathrm{cm}^2$ would not be viable for a transistor.) Over time, however, we have observed substantial changes in the densities obtained for a fixed GaTe cell temperature and soak time. In our experience, GaTe is not as stable a source as Si, probably because of its higher vapor pressure and source depletion.

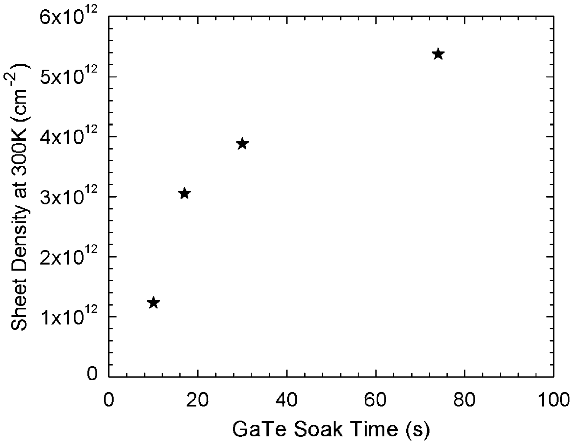

Fig. 3. Room-temperature sheet-carrier density as a function of GaTe soak time for Te delta-doped HEMT structures grown within a four-day period.

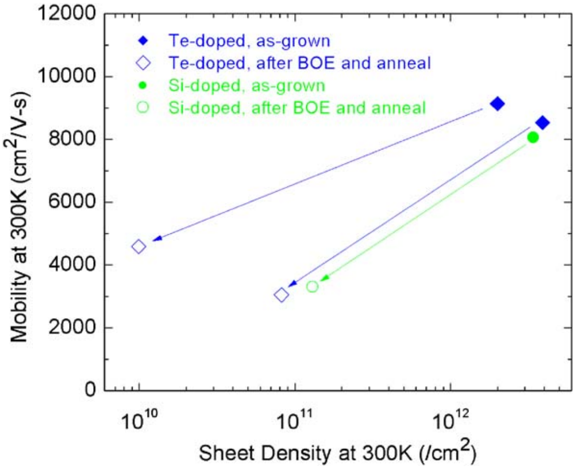

Fig. 4. Electron mobility and sheet carrier density for Te- and Si-doped InP HEMT structures before and after fluorination via exposure to BOE and annealing.

We selected a conventional Te-doped structure and a Te delta-doped structure for the fluorination experiments. For comparison, we also tested a Si delta-doped InP HEMT with a layer structure, carrier density, and mobility that were nearly identical to the Te delta-doped sample. The transport characteristics before and after fluorination are shown in Fig. 4. It is clear that Te-doped HEMT structures suffer from the same Si deactivation problem as Si-doped HEMTs, with the carrier densities decreasing by more than an order of magnitude.

Yamamoto et al. investigated the effects of fluorine on n-InAlAs (Si- and Sn-doped) and p-InAlAs (Be-doped) [13]. They observed no evidence of acceptor passivation in the p-InAlAs but observed substantial deactivation and mobility degradation in both the Si- and Sn-doped n-InAlAs. They proposed a model in which fluorine atoms react with donor impurities, forming F^- ions. These ions decrease the free electron concentration and form a scattering center, reducing the mobility. Si and Sn atoms must reside on In or Al sites to act as donors. In contrast, Te donor atoms reside on As sites. Our findings support the Yamamoto model, independent of the donor species and the sublattice in which they are substitutionally inserted [13]. We note that Tanabe et al. were able to avoid F-deactivation in InP HEMTs by inserting Si delta doping in the center of a 20 Å mismatched AlGaAs layer [14]. A similar approach should work for Te doping, especially considering the successful Te-doping of InGaAs/AlGaAs HEMTs [8].

4. Conclusions

We have demonstrated that Te (in the form of GaTe) can be used to dope InP HEMT structures grown by MBE. Both conventional and delta-doping yielded samples with reasonable mobilities and carrier concentrations without optimization of the growth parameters. Based upon these findings, GaTe appears to be a viable doping source for InP HEMTs. This could be useful as conventional InGaAs/InAlAs HEMT structures are modified to include mixed arsenide–antimonide layers, often grown in MBE machines without a Si source. Unfortunately, Te-doped InAlAs suffers from the same fluorine-induced deactivation as Si-doped InAlAs.

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