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Transport properties of InAs epilayers grown on GaAs substrates by using the prelayer technique

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The InAs/GaAs system has become one of the most popular materials for its application in high-speed devices and optolectronic devices [1]. However InAs grown on GaAs is a highly lattice-mismatched system and the lattice mismatch is relaxed into defects through the creation of dislocation in the epilayers. Therefore it is extremely important to accommodate these dislocations at the interface in order to reduce significantly defect densities in the epilayers. Previously, transport studies [2, 3] have been performed on InAs grown directly on GaAs under As-rich conditions. The strain is first relieved partly by the formation of a coherent island surface, and then by formation of 60 ° mixed-type misfit dislocations and stacking faults at the island edges. So, a rough cross-hatched surface and high densities of bulk defects exist in the InAs thin film. So far studies have shown that the dislocation density in these InAs epilayers on GaAs increases with decreasing thickness and most of the defects are found in approximately the first 300 nm of InAs epilayers [4, 5]. The polar electron-phonon interaction is shown to be the most important mobility limiting mechanism at high temperatures for bulk InAs. The high impurity concentration present in bulk InAs, on the other hand, leads to the ionized impurity scattering of carriers at low temperatures. Similar interpretations have also been used for the explanation of electronic properties of thin InAs epilayers [6]. Misfit and threading dislocations in InAs epilayers have been reported [7] to have a deleterious impact on the electronic properties. Dislocations act as nonradiative recombination centers in InAs and other direct gap semiconductors. Threading and misfit dislocations have also associated strain fields around them, which can interact with and scatter electrons. It can be surmised that strain field related scattering is also significant.

Our group reported interesting results [8–10] on initial InAs grown directly on a GaAs substrate. It was found that the strain is fully relaxed within 7 nm thick InAs layers under In-rich conditions with low threading dislocations, where only 90 ° mixed-type misfit dislocations form at the interface. The results also show that the new way to obtain high quality InAs epilayers on GaAs substrate is a two-step growth process: InAs grown directly on a GaAs substrate as prelayers under In-rich conditions, and then growth of InAs layers on such prelayers under As-rich conditions [8].

In this letter, using Hall effect measurements, we investigate the electronic transport properties of InAs grown on GaAs by using the new prelayers technique.

The InAs growth was carried out in a V80H molecular beam expitaxy (MBE) system. The growth process was investigated by *in situ* reflection high-energy electron diffraction (RHEED). The growth was started with 200 nm thick GaAs buffer layers on a GaAs (001) substrate at 580 °C. Six different samples were grown on the 2 °-misoriented (001) GaAs substrates for Hall effect measurements. Fig. 1 is a schematic diagram of the multilayer structure. Sample V_1 was grown with a 40 nm thick InAs epilayer on GaAs substrate under In-rich conditions at 500 °C. For samples V_2–V_6, the first InAs was 20 nm thick under In-rich conditions at 500 °C. The InAs epilayers were then continuously grown under As-rich conditions at 500 °C, which included the undoped InAs layers and the doped InAs layers. The thickness of the undoped InAs layers was different for samples V_2–V_6. The thickness of the doped InAs layers for samples V_2–V_6 was the same. Details of growth parameters for these samples are shown in Table I. The InAs grown on GaAs substrates under In-rich conditions maintains two-dimensional growth throughout the entire growth process of InAs with (4×2) reconstruction. For InAs layers grown under As-rich conditions after InAs prelayers growth, streaky RHEED patterns with (2×4) reconstruction are observed, which also indicates a two-dimensional growth mode [9]. Fig. 2 shows $\frac{1}{4}$ and $\frac{1}{2}$ order lines associated with In-rich and As-rich surfaces.

It is found that the total quality of InAs layers is higher at the higher growth temperature for InAs prelayers grown under In-rich conditions [11]. In order to obtain a high quality of InAs prelayers under In-rich conditions, we have grown InAs layers at temperatures of 500, 450, 380, and 350 °C. But the higher growth temperature has a narrower range of III/V ratio to maintain the two-dimensional growth mode. When the growth temperature for InAs prelayers under In-rich conditions is over 500 °C, it is very hard to keep the two-dimensional growth mode in a narrow range of III/V ratio. So, all samples are grown under the optimized growth conditions.

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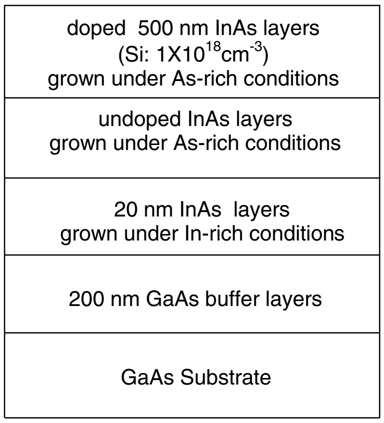

Figure 1 Scheme of multilayer structure grown by MBE.

Hall effect measurements use the well-known Van der Pauw technique at low electric fields. All the undoped samples exhibit n-type conduction. Typical results of all samples reported here are summarized in Table II. The sample V_1, which was grown under In-rich conditions, gave the lowest mobility and highest carrier concentration at 300 K (the room temperature). Our results [8] show that the strain is fully relaxed within a 7 nm thick InAs layer under In-rich conditions with threading dislocations. So this layer consists of high-density 90 ° mixed-type misfit dislocations and Indium anti-site defects. Dislocations with edge components are known to capture electrons and form a space-charge region [12]. The resulting potential scatters the carriers and reduces the mobility. The Indium anti-site defects also results in very low effective mobility and high carrier concentrations [11]. The ionized impurity scattering is the dominant mechanism for limiting mobility at 77 K (the liquid nitrogen temperature). The high density of ionized impurity in this layer hinders measurement of sample V_1 at 77 K.

The dependence of mobility and carrier concentrations of InAs epilayers on the thickness of undoped InAs layers is shown in Fig. 3a and b at 300 and 77 K. The combined ionized impurity and optical phonon scattering model in the InAs epilayers seems to fail in accounting for the trends [13]. Wieder and Wang [14, 15] used a two-layer model to explain the temperature dependence of electron mobility in the relatively thicker InAs epilayers. Parallel conduction arises from a variation of conductivity with depth in the epilayers. For thick InAs epilayers grown on GaAs substrate, the existence of three spatial regions contributing to conduction was confirmed from the etching experiment [5]. The three layers are distinguished as surface layers (s), bulk layers (b), and interface layers (i). Recent research [13] indicates that the contribution to the Hall mobility of electrons from bulk and surface layers is similar. So the two-layer model (interface layers and bulk layers) can be used to explain our experimental results. According to the two-layer parallel conduction model [13–15], the apparent Hall mobility is as follows:

$$\mu = \frac{\mu_{\mathrm{b}}^2\left(\frac{n_{\mathrm{b}}}{n_{\mathrm{i}}}\right) + \mu_{\mathrm{i}}^2\left(\frac{d_{\mathrm{i}}}{d-d_{\mathrm{i}}}\right)}{\mu_{\mathrm{b}}\left(\frac{n_{\mathrm{b}}}{n_{\mathrm{i}}}\right) + \mu_{\mathrm{i}}\left(\frac{d_{\mathrm{i}}}{d-d_{\mathrm{i}}}\right)} \tag{1}$$

where μ_{b} and n_{b} are the electron mobility and density of the bulk layers in the InAs epilayers, respectively. μ_{i} and n_{i} are the electron mobility and density of the interface layer respectively. d is the total thickness of the InAs epilayers, d_{i} is the thickness of the interface layers.

For the samples V_2–V_6, the growth conditions are similar, only the thickness of the undoped InAs layers is different. Samples V_3–V_6 have undoped InAs layers. By doping Si far from the interface of InAs prelayers, the ionized impurity scattering reduces μ_{i} and μ_{b} reduce, but $n_{\mathrm{b}}/n_{\mathrm{i}}$ increases rapidly. From the results of sample V_1, we know $\mu_{\mathrm{i}} \ll \mu_{\mathrm{b}}$. According to Equation 1, the apparent mobility will be dominated by the bulk layer electrons. For sample V_2, without the undoped InAs layers, first InAs was grown 20 nm thick under In-rich conditions, then InAs epilayers continuously grown under As-rich conditions with Si doping. As we know, the quality of InAs grown under In-rich conditions is very poor. The differences in ionic radius between In and Si will result in new defects and 60 ° mixed-type misfit dislocations at the beginning of the growth of InAs grown under As-rich conditions [16]. This causes samples (V_3–V_6) with undoped InAs layers to have higher electron mobility than that of the sample without undoped InAs layers (sample V_2). From Equation 1 we also see that $d_{\mathrm{i}}/(d - d_{\mathrm{i}})$ reduces when d increases. The contribution of electrons from the bulk layer weighs more heavily than that from the interface layer [13]. Because $\mu_{\mathrm{i}} \ll \mu_{\mathrm{b}}$, the apparent electron mobility tends to be nearly equal to μ_{b}. So the apparent

TABLE I Detailed growth parameters for indicated samples under indicated conditions

	InAs growth under In-rich conditions			InAs growth under As-rich conditions			
					Growth thickness (nm)		
Sample	Growth temp. (°C)	Growth thickness (nm)	The flux ratio of V/III	Growth temp. (°C)	Undoped InAs layers	Doped InAs layers (Si: 1 × 10^{18} cm^{-3})	The flux ratio of V/III
V_1	500	40	8				
V_2	500	20	8	500		500	10–23
V_3	500	20	8	500	30	500	10–23
V_4	500	20	8	500	50	500	10–23
V_5	500	20	8	500	70	500	10–23
V_6	500	20	8	500	100	500	10–23

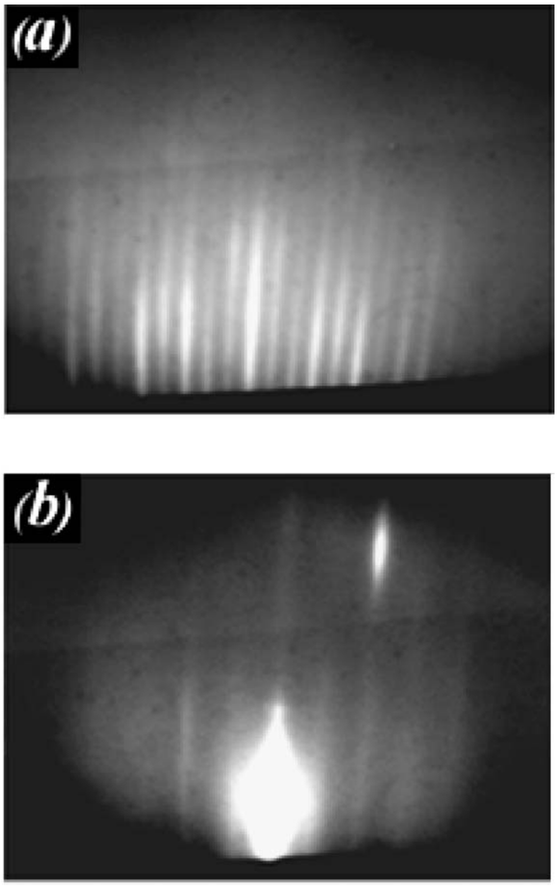

Figure 2 RHEED patterns of (4 × 2) indium rich reconstructions and (2 × 4) arsenic rich reconstructions observed on the (001) GaAs substrate along [110] azimuth.

electron mobility will increase with increasing total InAs epilayers, which explain the electron mobility increasing in samples V_2–V_6.

Samples V_2–V_6 have different thickness of undoped InAs layers. But the electron mobility shown in Fig. 3 at 300 and 77 K reaches saturation for thickness greater than about 70 nm. From Equation 1, we can find d_i (the thickness of interface layers), which includes the thickness of prelayers (20 nm) and InAs epilayers grown under As-rich conditions (70 nm). Our d_i is about 90 nm, which is also extremely thin. In general, d_i of the InAs epilayer is thicker than 300 nm when grown directly on GaAs under As-rich conditions [4, 13].

The dotted lines in Fig. 3 show carrier concentration as a function of thickness of undoped InAs layers at 300 and 77 K. There is a drop in carrier concentration away from the interface, and at a thickness of 70 nm, carrier concentration also appears to reach a saturation value of 1.1×10^{17} cm^{-3} at 77 and 300 K. The thickness variation of n(x) correlates well with the dislocation density. A very high dislocation density exists near the interface, which drops steeply away from the interface. Thus it is likely that carrier generation is defect related [7]. Gopal *et al.* [17] have proposed that the high interfacial sheet carrier density could be caused by a structural donor source at the intersection of misfit dislocation at the InAs/GaP interface and have demonstrated one-to-one correspondence between density of the intersection sites and the observed N_s. The strong thickness dependence of the carrier concentration suggests that the InAs/GaAs heterointerface is the origin of the high donor concentration. The high donor concentration seems be limited in the 90 nm InAs epilayers.

TABLE II The Hall mobility and carrier concentration of the InAs epilayers grown on (001) GaAs substrates at 300 and 77 K

	300 K		77 K	
Sample	μ (cm^2/V s)	$n \times 10^{18}$ (cm^{-3})	μ (cm^2/V s)	$n \times 10^{18}$ (cm^{-3})
V_1	761	2.82	——	
V_2	5627	0.2	6987	0.167
V_3	6753	0.17	7745	0.148
V_4	8602	0.1498	10085	0.133
V_5	8663	0.126	12343	0.110
V_6	8686	0.12	12594	0.105

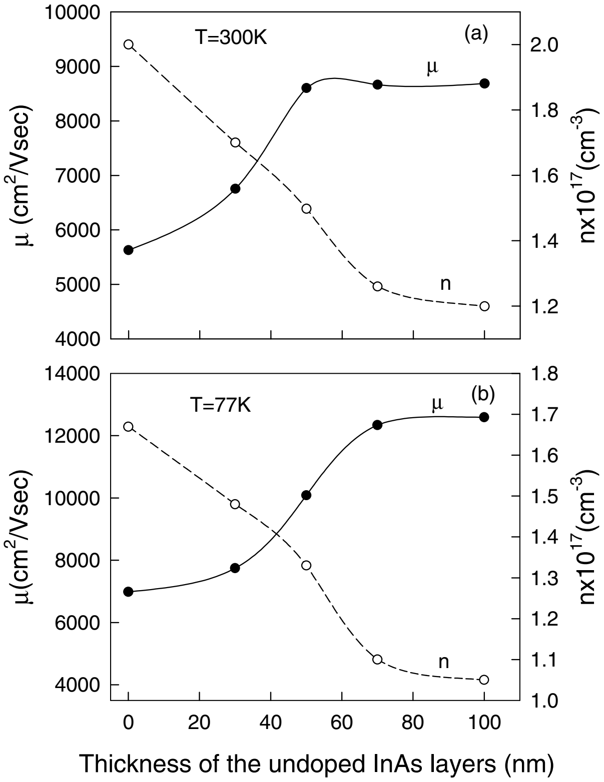

Figure 3 The dependence of the mobility and carrier concentration of the InAs epilayers on the undoped InAs epilayers thickness at (a) 300 and (b) 77 K.

In conclusion, the transport properties of the InAs epilayers grown on GaAs substrate by the new prelayer technique have been investigated by Hall effect measurements. A two-layer mode has been applied to account for the doping effect on the Hall mobility in the InAs epilayers. The electron mobility and carrier concentration at 300 and 77 K reaches saturation for thickness of unopded InAs layers greater than 70 nm. A detailed discussion of dislocation scattering, ionized impurity scattering, phonon scattering and structural features etc. on the InAs epilayers grown on GaAs substrates by this new prelayer technique requires further study.

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