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Improving the mobility of an $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ inverted modulation-doped structure by inserting a strained InAs quantum well

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The mobility of two-dimensional electrons in an $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ inverted modulation-doped structure improved by inserting an InAs quantum well into the InGaAs channel. This letter addresses the main cause of this mobility improvement. By optimizing the thickness of the InAs quantum well, its distance from the underlying InAlAs spacer layer, and the InAlAs spacer-layer thickness, maximum mobilities of 16 500 cm^2/V s at 300 K and 155 000 cm^2/V s at 10 K are attained. The improvement in mobility is attributed to a decrease in scattering caused by ionized impurities, interface-roughness, and trap impurities. This decrease is a result of the superior confinement of two-dimensional electron gas in the InAs quantum well.

The high-frequency and low-noise performance of high electron mobility transistors (HEMTs) fabricated from InAlAs/InGaAs modulation-doped structures are better than those of AlGaAs/GaAs HEMTs.[1,2] This superior performance results from higher electron mobility, saturation drift velocity, and sheet-carrier density in the InAlAs/InGaAs two-dimensional electron gas (2DEG) system. An inverted HEMT (*i*-HEMT), which has a channel layer located on the carrier-supply layer, would be expected to perform better than a normal HEMT (*n*-HEMT) due to the superior electron confinement and the shorter distance between the gate and the 2DEG.[3–5] However, the performance of an inverted HEMT is limited by the lower mobility of 2DEG formed at the inverted heterostructure. This lower mobility is assumed to be a result of the poor structural quality of the inverted interface, Si surface segregation into the channel, and the trapping of ambient impurities at the inverted interface.[4] Therefore, *i*-HEMTs have been less actively investigated than *n*-HEMTs.

We have recently attained improved 2DEG mobility in $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ inverted modulation-doped (*i*-MD) structures by inserting an InAs quantum well into the InGaAs channel layer (InAs-inserted channel).[6–8] 2DEG mobility for the InAs-inserted-channel *i*-MD structure at 300 K is 35% higher than that of the normal modulation-doped (*n*-MD) structure without an InAs quantum well, and is equal to that of the InAs-inserted-channel *n*-MD structure. In this letter, we analyze in detail the electron transport properties of the InAs-inserted-channel *i*-MD structure by Hall measurement. In this way, we have identified the main cause of the 2DEG mobility improvement.

Figure 1 shows the InAs-inserted-channel *i*-MD structure. The heterostructure used in this study was grown by molecular beam epitaxy (MBE) on an Fe-doped semi-insulating (100) InP substrate. All InGaAs and InAlAs layers were lattice matched to InP, and the growth temperature for all layers was set at about 300 °C, since the critical thickness increases at lower growth temperatures.[9] Based on results in two of our previous reports,[6,7] we fixed the InAs quantum-well thickness L_w at 40 Å and the insertion position Z (the distance between the InAlAs spacer layer and the InAs quantum well) at 25 Å. The doping density of the InAlAs carrier-supply layer was 4×10^{18} cm^{-3}.

During Hall-effect measurements, the sample was kept in the dark. The measurements were performed using the standard van der Pauw technique to obtain the mobility μ and the sheet-carrier density n_s of the 2DEG as functions of temperature in the range from 10 to 300 K. In addition, the effective mass m^* of 2DEG in the InAs-inserted-channel and conventional *i*-MD structures was determined by Shubnikov–de Haas measurement. It was found that $m^*=0.044m_0$ at $n_s=2.08\times10^{12}$ cm^{-2} for the InAs-inserted-channel *i*-MD structure and $m^*=0.051m_0$ at $n_s=1.88\times10^{12}$ cm^{-2} for the conventional one. The effective mass of the InAs-inserted-channel *i*-MD structure was about 10% smaller than that of the conventional one. Details of SdH measurement are described elsewhere.[8]

Figure 2 shows results of Hall measurements taken in the temperature range from 10 to 300 K. The spacer-layer thickness for each of these samples is 100 Å. For the InAs-inserted-channel *i*-MD structure, we attained a mobility of 16 500 cm^2/V s at a $n_s=1.96\times10^{12}$ cm^{-2} at 300 K. Furthermore, a low-temperature (10 K) mobility of 155 000 cm^2/V s

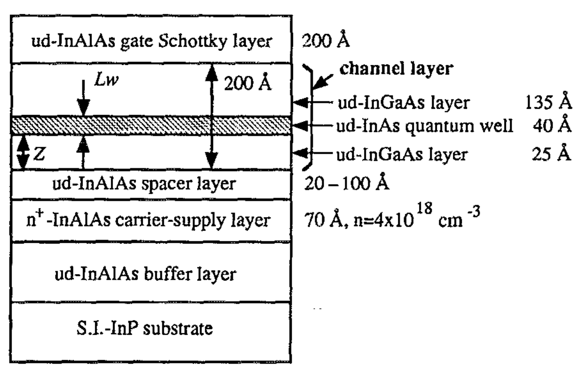

FIG. 1. The InAs-inserted-channel inverted modulation-doped structure.

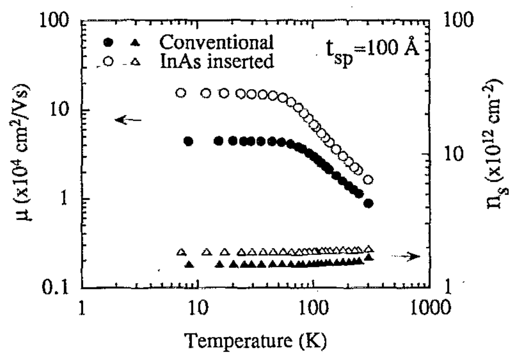

FIG. 2. 2DEG mobility dependence on temperature (6–300 K) in the InAs-inserted-channel and conventional inverted modulation-doped structures.

was reached at a n_s of 1.86×10^{12} cm^{-2}. These values are 85% higher at 300 K and 250% higher at 10 K than those of the conventional i-MD structure. In particular, the low-temperature mobility is higher than anything reported previously for InAlAs/InGaAs normal and inverted MD structures. Below 30 K, the mobility saturates in both the InAs-inserted-channel and conventional i-MD structures. This shows that the mobility at low temperatures is limited by temperature-independent scattering mechanisms such as alloy disorder and ionized impurities.[10] However, the influence of alloy-disorder scattering is assumed to be negligible because the mobility of the conventional i-MD structure is far smaller than that of the $In_{0.53}Ga_{0.47}As$/InP i-MD structure, which is dominated by alloy-disorder scattering ($\mu\sim$190 000 cm^2/V s at 4.2 K).[11] Above 100 K, the mobility exhibits an exponential decrease, indicating that the transport properties at high temperatures are dominated by polar-phonon scattering. The values observed at these temperatures vary at $T^{-1.27\pm0.04}$ for the InAs-inserted-channel and $T^{-0.99\pm0.03}$ for conventional i-MD structures. The temperature dependence of InAs-inserted-channel i-MD structures is comparable to that of pseudomorphic InAlAs/InGaAs n-MD structures.[12] On the other hand, as will be discussed later in more detail, the weaker temperature dependence of the conventional i-MD structure can probably be attributed to the effects of increased ionized-impurity scattering.

Figure 3 shows the mobility and sheet-carrier density as functions of the spacer-layer thickness t_{sp} at 300 and 10 K. A sharp increase in 2DEG mobility is observed when increasing the spacer layer thickness from 20 to 100 Å. This is due to reduced Coulomb scattering between the electrons in the 2DEG and the ionized donors in the InAlAs carrier-supply layer. In addition, Coulomb scattering caused by the silicon ionized donor moving into the InAlAs spacer layer and the InGaAs channel layer by surface segregation can be reduced. This shows that ionized-impurity scattering is the dominant scattering mechanism at low temperatures in both the InAs-inserted-channel and conventional i-MD structures.

Figure 4 shows the calculated 2DEG distribution in the conventional and InAs-inserted-channel i-MD structures at 300 K, which was derived by solving the Shrödinger and Poisson equations self-consistently. The conventional and

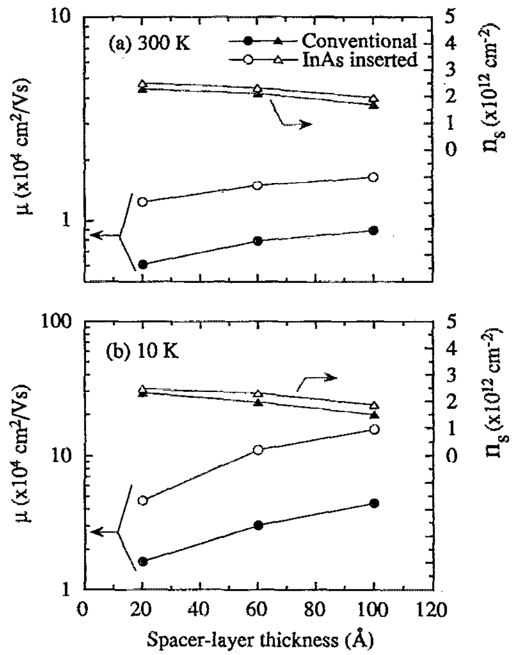

FIG. 3. Mobility and sheet-carrier density as functions of spacer-layer thickness t_{sp} at (a) 300 K and (b) 10 K.

InAs-inserted-channel i-MD structures are identical, except for the InAs quantum well inserted in the InGaAs channel layer. Almost all of the 2DEG in the InAs-inserted-channel i-MD structure is formed in this InAs quantum well. The distance between the peak position of the 2DEG and the InAlAs/InGaAs interface is about 15 Å longer in the InAs-

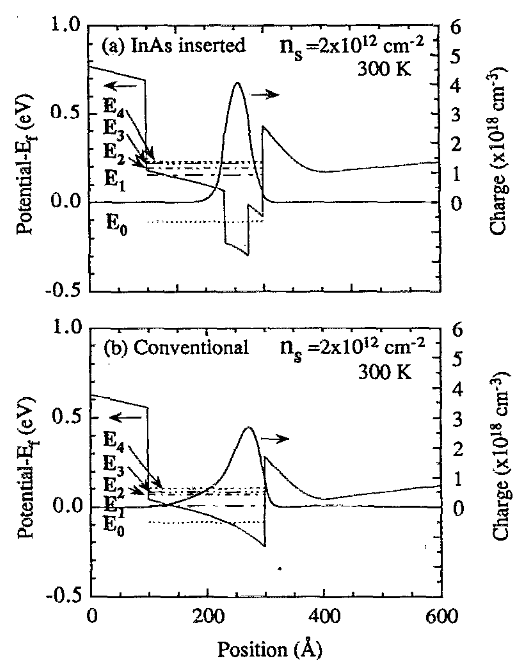

FIG. 4. Calculated 2DEG distribution and subband levels in the (a) InAs-inserted-channel structure and (b) conventional inverted modulation-doped structure at 300 K.

inserted-channel i-MD structure as a result of optimizing the insertion position. This indicates that the scattering caused by ionized donors in the InAlAs carrier-supply layer, as well as Si surface segregation, is reduced. However, this phenomenon by itself cannot explain the remarkably improved mobility in the InAs-inserted-channel i-MD structure. This is because even the mobility at 10 K of the InAs-inserted-channel i-MD structure with a t_{sp} of 60 Å is about 150% higher than that of the conventional n-MD structure with a t_{sp} of 100 Å. We assume that another reason for the improved mobility is related to the decrease in scattering caused by interface roughness and trap impurities. This is because the degree of 2DEG distribution around the InAlAs/InGaAs interface in the InAs-inserted-channel i-MD structure is reduced to about one-third due to electron confinement in the InAs quantum well (see Fig. 4). In addition, there are other possible reasons for the improvement in 2DEG mobility in the InAs-inserted-channel i-MD structure. One is a reduction of about 10% in the effective mass of 2DEG.[8] The other is a decrease in alloy-disorder scattering due to the confinement of 2DEG in the InAs quantum well. However, as mentioned above, the influence of the alloy-disorder scattering is negligible because ionized-impurity scattering dominates at low temperatures. We consider the influence of these two factors on mobility improvement to be minimal. Thus, we assume that the primary cause of improved mobility in these structures is the suppression of ionized-impurity scattering. A secondary cause is the suppression of scattering at the InAlAs/InGaAs interface.

In conclusion, we have shown that the mobility of two-dimensional electrons in an InAlAs/InGaAs inverted modulation-doped structure can be improved by inserting an InAs quantum well into the InGaAs channel. When this InAs quantum well is 40 Å thick and inserted 25 Å from the InAlAs spacer layer, a maximum mobility of 16 500 cm^2/V s at 300 K and 155 000 cm^2/V s at 10 K were attained. These values are 85% and 250% higher, respectively, than those of the conventional i-MD structure without an InAs quantum well. The reduced mobility at low temperatures in the InAlAs/InGaAs i-MD structure is limited primarily by ionized-impurity scattering, and secondarily by scattering at the InAlAs/InGaAs interface. Thus, mobility improvement in InAs-inserted-channel i-MD structures is attributed to a decrease in the scattering caused by ionized impurities, interface roughness, and trap impurities. This decrease results from the superior confinement of two-dimensional electron gas in the InAs quantum well.

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