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Invited

Super-Doped Structure

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Super-doped structure (SDS) is a unique short-period AlAs/GaAs superlattice, in which donor impurities (Si) are only doped into the GaAs mid-layer. Since Si atoms behave as simple shallow donors in this superlattice the electron concentration dramatically increases, compared with n-type AlGaAs alloys. Two dimensional electron gas FETs with the present superlattice have shown an excellent threshold voltage stability with operating temperature change, as well as high transconductance capability.

1. Introduction

AlGaAs, an important semiconductor alloy for two dimensional electron gas FETs (2DEGFETs or HEMTs) and laser diodes, has a serious problem in that any donor impurity behaves as a deep center (DX center)[1] for specific AlAs mole fraction ($0.25 < x < 0.7$), regardless of growth methods[2] (i.e., LPE, MOCVD and MBE) and growth conditions. The electron concentration reported, therefore, is less than 2×10^{18} cm^{-3}, even at room temperature, and decreases rapidly with temperature decrease.[3] Since, in 2DEGFETs, n-type AlGaAs has been used for an electron supplying layer material, this phenomenon causes a threshold voltage change with operating temperature change.[4] Moreover, electron trapping and detrapping at DX centers are nuisances for 2DEGFET operation. Transient response at low frequencies and I-V collapse[5] at a low temperature are mainly caused by DX centers.

Currently, a ballistic transistor has been proposed as an ultra high speed transistor. A preliminary device, using an n-type AlGaAs layer as a hot electron emitter, did not operate at 77 K, because electrons freeze out into DX centerns.[6]

Device applications described above require DX center elimination. Super-doped structure (SDS), developed in our group,[7] gives the first success in eliminating DX centers. In this paper, SDS concept, properties and applications are presented.

2. Super-Doping Concept

IV group elements (Si, Ge and Sn) and VI group elements (S, Se and Te), which are known as simple shallow donor impurities in GaAs with about 6 meV activation energies, anomalously deepen their energy level in $Al_xGa_{1-x}As$ ($0.25 < x < 0.7$).[2] For $Al_{0.4}Ga_{0.6}As$, the Si activation energy, estimated from Hall measurements, reaches 150 meV. Generally, impurity level deepening means captured electron localization around the impurity. DX ceter Bohr radius was calculated based upon a hydrogen like model. It is not accurate, but is sufficient for estimating the localization extent. The calculated radius was 5 A for 150 meV DX center, which is very localized, compared with 100 A for a simple shallow donor. It was postulated that some kind of structural anomaly existed inside the Bohr radius and caused localization. The difference between GaAs and AlGaAs in this region is the second nearest atom configuration of a Si atom; in GaAs, Ga atoms occupy these sites, whereas, in AlGaAs, both Ga and Al atoms could simultaneously occupy these sites as shown in Fig. 1(a). It is expected that such an alloy randomness affects donor energy level. Thus, we introduced super-doped structure (SDS), a short period AlAs/GaAs superlattice, in which Si atoms were only doped in the mid-layer of GaAs, 5 A from AlAs (Fig. 1(b)). In this structure, the Si atom configuration is the same as that in GaAs.

A super-doped structure energy band is shown in Fig. 2. The free electrons, generated from Si donors in the GaAs layers, spread over the whole superlattice layer, forming a mini-band above the GaAs band edge, since the AlAs barrier width (15 A) is thin enough for

electron tunnelling. The valence mini-band is formed in the same manner. The superlattice band gap is adjustable by both GaAs and AlAs thicknesses.

Figure 3 shows the relation of the conduction mini-band energy with the superlattice period, where AlAs and GaAs thicknesses are chosen to be the same. Calculations were made using a Kronig-Penny model, assuming that electrons, with different k-space symmetry (Γ, L and X), were independent each other and were subject to the periodic potential originating from the same symmetry GaAs and AlAs energy levels. Reduction in the period raises the mini-band minimum, and thereby increases the superlattice band gap. At 25 A mini-band minimum crosses over the L mini-band minimum, due to the larger effective mass and the smaller energy barrier of L band electrons. Although the Kronig-Penny model is inaccurate for an extremely short period superlattice, the result in Fig. 3 demonstrates that superlattice can be used instead of AlGaAs alloys.

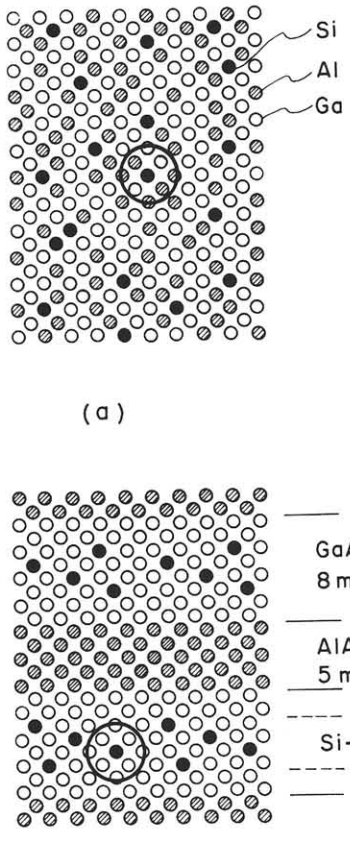

Fig. 1 Si doped Al-Ga-As system structures; (a) conventional AlGaAs alloy, (b) super-doped structure. Large circles represent Bohr circles with 5 A radius.

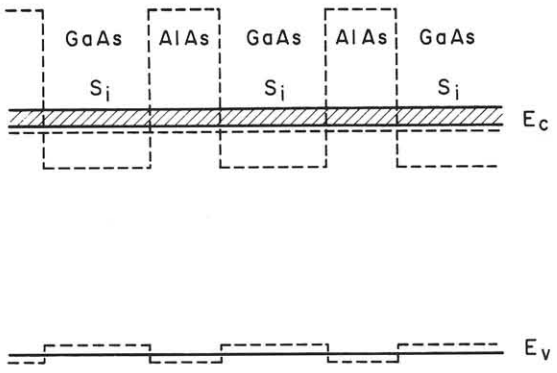

Fig. 2 Super-doped structure energy band.

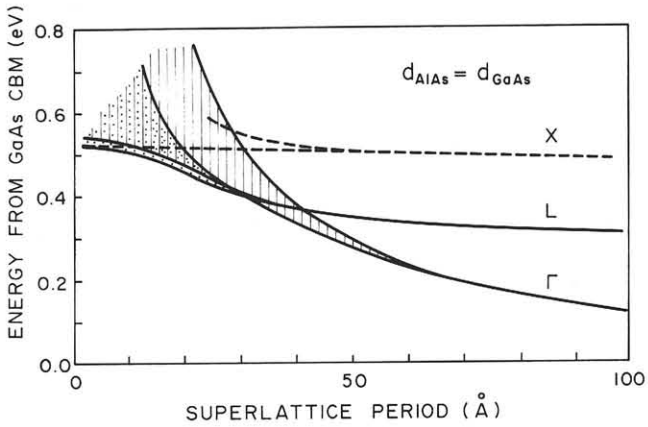

Fig. 3 Γ, L and X mini-band energy dependences on superlattice period. AlAs and GaAs thicknesses are the same.

3. SDS Properties

Super-doped structures were grown by a modified Riber 2300 P MBE machine with desk-top computor control. The superlattice period was 37 A with 15 A AlAs and 22 A GaAs layers. Si atoms were doped in the 12 A GaAs mid-layer. The Si concentration averaged in a 0.5 um SDS layer was 1×10^{18} cm^{-3}. The SDS band gap energy was determined from photoluminescence measurement. Figure 4 shows the electron concentration dependence on temperature obtained from Hall measurements. For comparison, results for a conventional Si doped $Al_{0.34}Ga_{0.66}As$ alloy with nearly the same band gap as the SDS is given. The alloy electron concentration decreased rapidly with decreasing temperature, due to DX centers. On the contrary, the SDS electron concentration varied moderately with 7 meV activation energy, indicating that Si atoms in SDS act as simple shallow donors. Consequently, the electron concentrations at 300 K and 77 K increases 10 times and

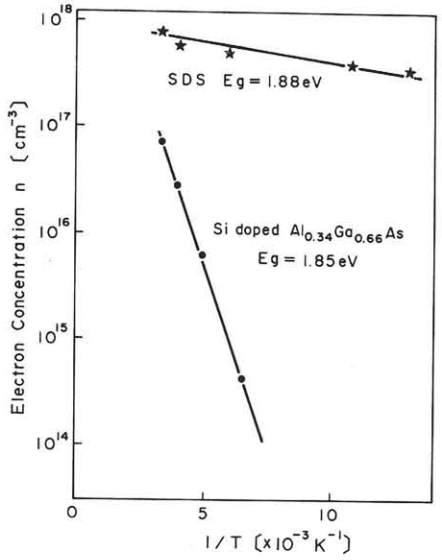

Fig. 4 Electron concentration dependence on temperature for SDS and Si doped $Al_{0.34}Ga_{0.66}As$.

10^5 times, respectively, compared with $Al_{0.34}Ga_{0.66}As$. To confirm the DX center elimination, DLTS measurements were conducted for three samples;[8] an SDS sample, an AlAs/GaAs superlattice with the same structure as SDS, excepting that Si atoms were doped only at GaAs/AlAs interfaces, and a Si doped $Al_{0.34}Ga_{0.66}As$ alloy. The second sample had exactly the same band structure as SDS, whereas the atom configuration around Si was quite different. A marked DX center signal reduction was obtained in SDS (Fig. 5). A large DX center signal in the interface-doped superlattice indicates whether Si acts as a shallow donor or a DX center depends on local configuration. This supports the super-doping concept. Further investigations on DX center have been conducted, in focusing on band structure and local configuration effects.[9]

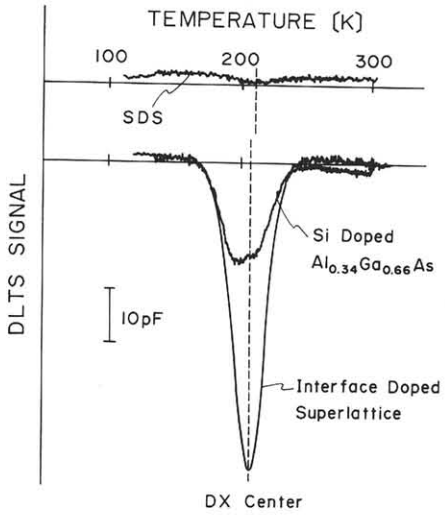

Fig. 5 DLTS signals for SDS, interface-doped superlattice and Si doped $Al_{0.34}Ga_{0.66}As$.

Another striking SDS property is high electron concentration. As shown in Fig. 6, the maximum electron concentration for the sample grown at 420 °C reaches 9×10^{18} cm^{-3}, 10 times greater than that for conventional alloys.

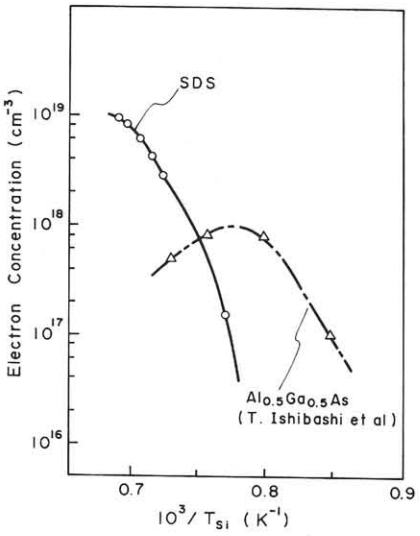

Fig. 6 Electron concentrations at room temperature for SDS and Si-doped $Al_{0.5}Ga_{0.5}As$.[3]

4. SDS Applications

Novel 2DEGFETs were fabricated using an SDS layer as an electron suppling layer. Figure 7 shows a prototype structure.[10] The average SDS layer doping level and thickness of were 2×10^{18} cm^{-3} and 120 A (3 periods), respectively. On the SDS layer, Si-doped GaAs and undoped AlAs layers were alternatively deposited,

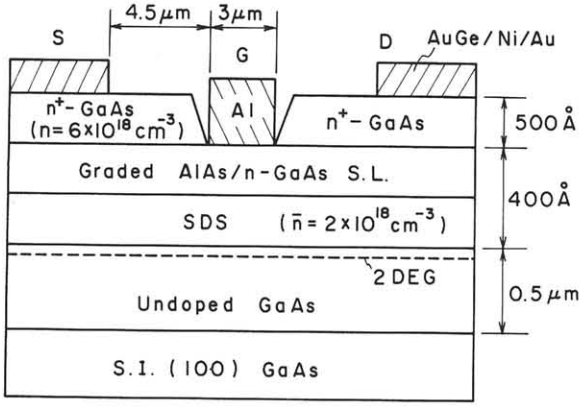

Fig. 7 SDS 2DEGFET structure.

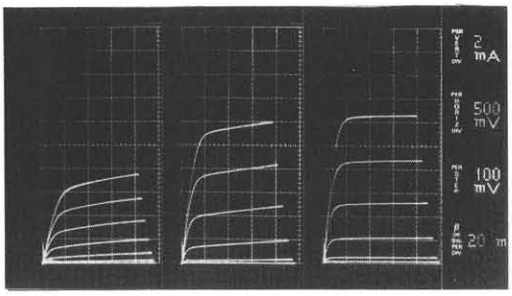

Fig. 8 I-V characteristics for 3 um-long gate SDS 2DEGFETs.

keeping AlAs thickness constant and increasing GaAs thickness step by step. Two dimensional electron existence at SDS and undoped GaAs heterointerface was confirmed by 4.2 °K Shubnikov-de Hass oscillation. Electron mobility and sheet carrier concentration at 77 °K were 89000 $cm^2/V.s$ and 8×10^{11} cm^{-2}, respectively. I-V characteristics for 3 um-long gate SDS 2DEGFETs at 300 °K, 77 °K in dark and 77 °K under room light illumination are shown in Fig. 8. Increases in transconductances at 77 °K reflect both low field electron mobility and high field saturation velocity enhancements. It is noted that the threshold voltages in three conditions are almost the same. Figure 9 shows threshold voltage changes with operating temperatures for the two kinds of 2DEGFETs. Apparently, threshold voltage stability for an SDS 2DEGFETs is superior to that for a conventional AlGaAs 2DEGFETs.[4] Such a difference arises from Si behavior; a shallow donor in SDS 2DEGFETs and a DX center in AlGaAs 2DEGFETs. Since 2DEGFETs operate at a markedly high speed at

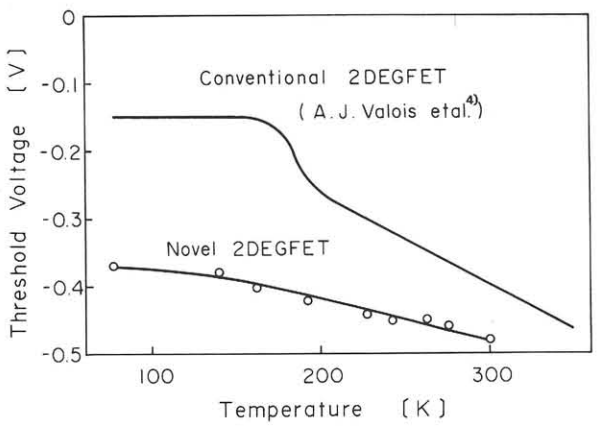

Fig. 9 Threshold voltage dependence on temperature for SDS 2DEGFET[9] and conventional AlGaAs 2DEGFET.[4]

cryogenetic temperature and since threshold voltage is an important parameter for logic applications, the present threshold stability with temperature is very attractive.

From the high doping characteristics for SDS (Fig. 6), extremely high transconductance is predicted.[10] A preliminary device with 8×10^{18} cm^{-3} doped SDS, however, has exhibited a large gate leakage. To realize high transconductance more than 700 mS/mm, further efforts are needed in structure designing and fabrication process optimization.

5. Conclusion

SDS is a unique superlattice which eliminates DX centers in AlGaAs alloys. It is expected that SDS will be useful not only for 2DEGFETs, but also for other devices, including ballistic transistors and high power laser diodes. Super-doping is a general concept and would be applied to other III-V and II-VI semiconductor alloys.

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