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The Doped Quantum Well Gate FET Fabricated by Low-Pressure MOCVD

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The doped quantum well FETs with $Al_{0.5}Ga_{0.5}As/GaAs$ heterostructures have been fabricated using low-pressure metalorganic chemical vapor deposition (LP-MOCVD) method. Conventional δ-doping thin layer in MODFET has been replaced with a doped $Al_{0.5}Ga_{0.5}As/GaAs/Al_{0.5}Ga_{0.5}As$ quantum well. Doping level in the GaAs quantum well was varied to observe the effects on the 2-DEG density in the channel. The corresponding I_{dsat} was increased from 12 mA to 27 mA at Vg=0V for increasing doping level in the well.

Two dimensional electron gas (2-DEG) FETs with N-AlGaAs and undoped GaAs heterostructures have shown better characteristics than MESFET with higher transconductance and lower noise figures.[1] This kind of structure, however, suffer from instabilities in persistent photoconductivity,[2] threshold voltage shift, and drain current collapse at low temperatures caused by DX center in $N\text{-}Al_xGa_{1-x}As$, especially those alloys with X>0.24.[3] Since the DX centers is postulated that is due to the coexistence of Al and donor atoms, the inferior characteristics of the MODFETs can be eliminated by the spatial separation of these atoms.[3] Based on this idea, improvements have been suggested by Baba[4] that the $AlAs/n^+\text{-}GaAs$ superlattice with Si doped only in the GaAs quantum wells instead of an N-AlGaAs layer effectively reduce these inferior characteristics. The threshold voltage changes with changes in temperature (77-300 K) and resulting from light illumination are effectively supressed (dV_T=0.1V). But, the effect of doping level in the doped GaAs quantum well on the 2-DEG density was not studied. In this paper, we studied the effects on 2-DEG density by varying doping level in the heterostructure (50A)$Al_{0.5}Ga_{0.5}As$/(50A)n-GaAs/(50A)$Al_{0.5}Ga_{0.5}As$ prepared by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) method. The doping level in GaAs quantum well was changed from $5X10^{17}$ to $2X10^{19}$ cm^{-3} to access the influences on 2-DEG density in the active channel. The measured data showed a soft saturated point of 2-DEG density at $4X10^{11}$ cm^{-2} with single doped-quantum well (D-QW) having doping level $5X10^{18}$ cm^{-3}. The further increase of the doping level (up to $2X10^{19}$ cm^{-3}) has been observed small effect in increasing the 2-DEG density and has the effects in reducing the drain and source excess resistances in the device structure. Finally, to demostrate the superior characteristics of this new structure, the D-QW FET's with geometry 5x250 um^2 were fabricated. Because of undoped $Al_{0.5}Ga_{0.5}As$ layer beneath the gate, this structure also found a benefit of increasing gate-drain breakdown voltage.

The layer structures were grown on (100) oriented Cr-O doped GaAs substrates by low-pressure MOCVD method. All layer structures

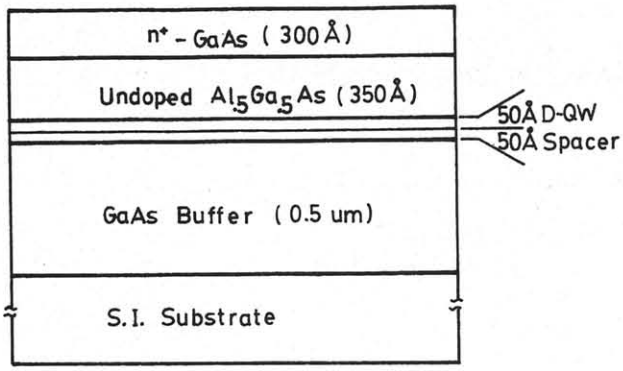

Fig.1. The layer structure of the quantum well modulation doped FET prepared by low pressure MOCVD.

were grown at 700 °C with chamber pressure 40 torr. Triethylgallium (TEG) and trimethylaluminum (TMA) were used as gallium and aluminum sources, respectively. The growth of undoped GaAs has been optimized and been characterized having electron mobility 55000 $cm^2/v.s$ with background impurity $1X10^{15}$ cm^{-3} (77 K) as the ordinary result. Growth of high quality $Al_xGa_{1-x}As$ has been achieved by bubbling the AsH_3 (15% diluted in H_2) into Ga-In-Al eutetic melt to remove the oxygen and moisture. The growth rate of GaAs and $Al_{0.5}Ga_{0.5}As$ were calibrated 240 A/min and 480 A/min, respectively. In investigating the effects of doping level of D-QW(s) on 2-DEG density, the layer structure is shown schematically in Fig.1. A 0.5 um GaAs buffer layer, 50 A $Al_{0.5}Ga_{0.5}As$ spacer layer, 50 A doped GaAs quantum well, 350 A undoped $Al_{0.5}Ga_{0.5}As$, and then 300 A n^+-GaAs contact layer ($n=2X10^{19}$ cm^{-3}). The doping concentration were $2X10^{19}$ cm^{-3} through $5X10^{17}$ cm^{-3} in GaAs QW that were calibricated from bulk growth of n-type GaAs with SiH_4 (500 ppm diluted in H_2) as the doping gas. Growth program is entirely performed by micro-computer controller, resulting in high reproducibility and reliability of the epitaxial growth process. Because of short period of growing $Al_{0.5}Ga_{0.5}As/n^+$ - $GaAs/Al_{0.5}Ga_{0.5}As$ structures (3 minutes) and the stop growth process (6 seconds) between transition, we considered the Al and Si inter-diffusion near the interface can be neglected. The electron mobility and sheet carrier density at room temperature and 77 K were estimated by Hall measurement for wafers in which the n^+-GaAs top layer were selectively etched away by citric acid solution. Square samples were cut from grown wafers, the sintered In dots served as the ohmic contacts. The prepared samples were then measured with the Van der Pauw measurement under 5000 gauss at room temperature and 77 K. The light sensitivity of these samples were also measured under tungsten lamp illumination. Figure 2 shows the band diagram and cross-sectional view of the doped QW FET structure. The alloyed AuGe/Ni were used for source and drain ohmic contacts and then the

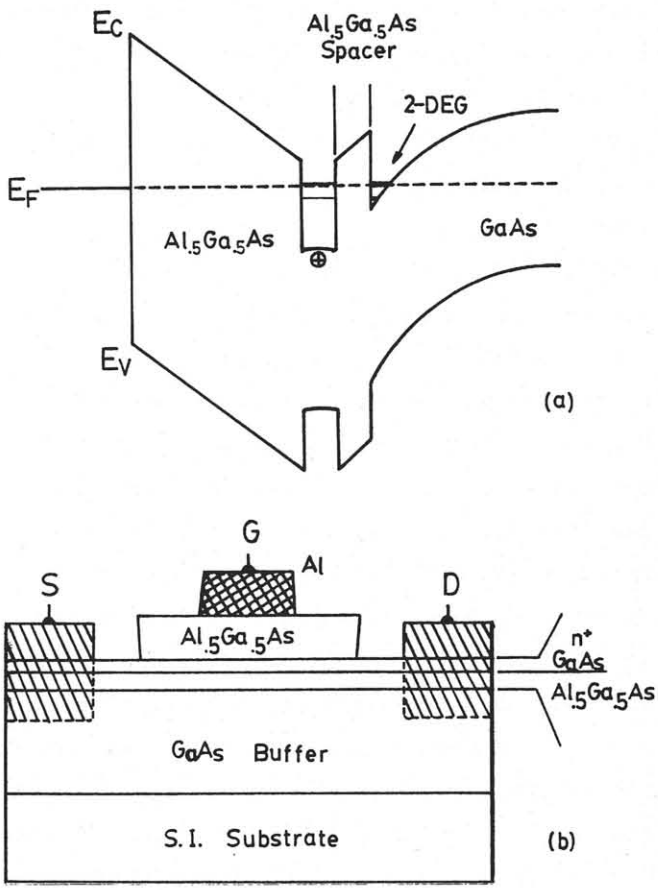

Fig.2. (a) Energy band diagram of the $Al_{0.5}Ga_{0.5}As/GaAs$ heterostructure that is heavily doped in the GaAs quantum well, (b) cross-sectional view of the structure.

Au evaporation on to it to reduce the bonding resistance. Conventional recessed gate process was performed with $2NH_4OH$: H_2O_2:$100H_2O$ solution. About 50 A undoped $Al_{0.5}Ga_{0.5}As$ layer beneath the n^+-GaAs layer was etched away to remove the ambiguous interface region and reduced the distance between Al gate and the active channel. With the structure, however, the fabricated devices exhibit no decrease of excess resistances. It were thought due to the difficulities of alloying Au-Ge through undoped AlGaAs layer, and the final device structure is shown in Fig.2(b). The doped GaAs QW then served as the contact layer for drain and source electrodes.

The results of Hall mobility and 2-DEG density measurements on single quantum-well modulation doped samples are shown in Fig.3. Both data measured at 300 K and 77 K showed the increasing 2-DEG density with increasing doping level in the GaAs quantum well, but start to saturate at doping level above $5X10^{18}$ cm^{-3}. This saturation effect is more clear observed at room temperature. For mobilities, a decreasing tendency with increasing doping level is obviously due to the increased impurity scattering via coulomb force of ionized Si atoms in the quantum well.

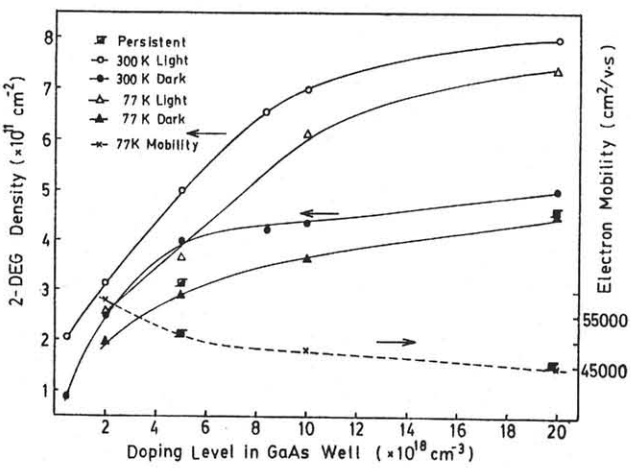

Fig.3. 2-DEG density and electron mobilities vs. doping level in GaAs well. The PPC effects were measured under 77 K and 2 minutes after light illumination was shut off.

Since the measured electron mobility decreasing with increasing doping level in the GaAs quantum well and the 2-DEG density became saturated at doping level $5X10^{18}$ cm^{-3}, we concluded that electron became to reside in the well by the attraction of positive charged ions in the well. For the doped single quantum well structures, the highest 2-DEG density was found to be $5X10^{11}$ cm^{-2} at the highest doping level $2X10^{19}$ cm^{-3} in the GaAs well. Figure 3 also shows the light sensitivity on mobilities and 2-DEG densities. The light illumination has substantially no effect on electron mobilities at 77 K, but an increase in 2-DEG density were clearly observed. It should be noted that the increased percentage quantity of 2-DEG density due to illumination is almost the same at a defined doping level and different temperatures (both 77 K and 300 K). Furthermore, the negligible PPC effect was also observed as shown in this figure. It proved that density of DX center is negligible in this structure.

Devices fabricated from layer structures (shown in Fig.2) have good characteristics as shown in Fig.4. The drain current collapse at 77 K associated with conventional MODFETs is not observed in our devices. On the contrary, a threefold increase in transconductance and the increase in drain current are attributed to the increase in electron drift velocity although the slightly decrease in 2-DEG density as described in Fig.3. The D-QW FETs then show their superior characteristics than conventional MODFETs by removing the DX centers from N-$Al_xGa_{1-x}As$ material. The threshold voltage shift between 300 K and 77 K in dark has been measured as 0.3V. But, when the devices shined with light, both large increase in transconductance and drain current were observed, and the threshold voltage shift was quite large (dV_T=0.8V) at 300 K and 77 K, which were different to the results of Baba.[4] When the light was shut off at cryo-

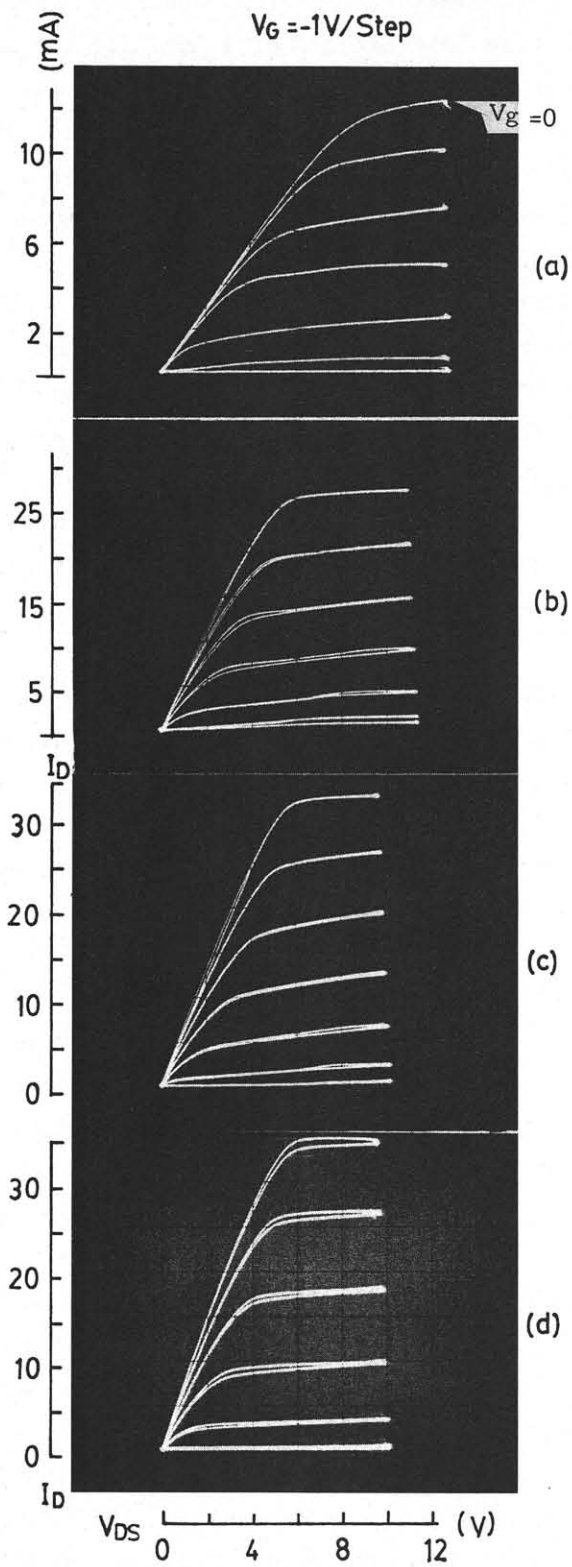

Fig.4. Photographs of I-V characteristics of the fabricated devices. (a) doped single QW FET with $n=1X10^{19}$ cm^{-3} in the well (300 K in dark), (b) doped single QW FET with $n=2X10^{19}$ cm^{-3} in the well (300 K in dark), (c)as in (a) but measured at 77 K in dark, (d) as in (c) but illuminated. In these devices, geometry is LXW=5X250 um^2.

genic temperature, the characteristics of these devices return to it's original shape similar to that a few seconds before illumination. The PPC effect were then not observed. We suggest that, from the above discussion, the large increase in transconductance and drain current may due to the photon generated electrons in the material that drift to the active channel and then contribute to the increase in 2-DEG density. The generated holes, however, drift toward the substrate and may increase the back-gating effect. The threshold voltage then shifted to more positive than in dark.

In summary, the doped quantum well FET structures are presented. Influences of doping level of D-QW on 2-DEG density were studied with (50A)$Al_{0.5}Ga_{0.5}As$/(50A)n^+-GaAs/(50A)$Al_{0.5}Ga_{0.5}As$ structures grown by LP-MOCVD. The 2-DEG density increased with increasing doping level in the well but start to increase softly at doping level above $5X10^{18}$ cm^{-3}. All the samples show small PPC effect at 77 K from results of Hall measurement or fabricated devices. Since undoped $Al_{0.5}Ga_{0.5}As$ layer beneath the gate, the gate-drain breakdown voltage was increased (30 V for the fabricated devices).

References

1) K. Tanaka, M. Ogawa, K. Togashi, H. Takakuwa, H. Ohke, M. Kanazawa, Y. Kato, and S. Watanabe " Low-Noise HEMT Using MOCVD", IEEE Trans. Electron Devices Vol. ED-33 (1986)2053
2) Marshall I. Nathan "Persistent Photoconductivity in AlGaAs/GaAs Modulation Doped Layers And Field Effect Transistors: A Review" Solid State Electron. Vol.29 (1986)167
3) Masashi Mizuta, Masami Tachikawa, Hiroshi Kukimoto, and Shigeru Minomura "Direct Evidence for the DX Center Being a Substitutional Donor in AlGaAs Alloy System" Jpn. J. Appl. Phys. Vol.24 (1985)L143
4) T. Baba, T. Mizutani, M. Ogawa, and K. Ohata "High Performance (AlAs/n-GaAs Superlattice)/GaAs 2DEGFETs With Stabilized Threshold Voltage" Jpn. J. Appl. Phys. Vol.23 (1984)L654