Growth and characterization of band gap engineered InGaAs/InAlAs/GaAs high-electron-mobility Quantum Well structure towards low leakage VLSI applications

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Abstract

Strained and scaled channel high-mobility quantum well structure has been grown in SVTA MBE for low leakage VLSI applications. Scaling and straining the channel enhances its band gap which is necessary for low leakage current. The structure has been characterized for such applications.

INTRODUCTION

The Recent trends in technology roadmap show that both academia and industries have strong orientation towards InGaAs and other low band gap materials for digital and advanced CMOS applications. A glimpse from the past shows that in 1981, a remarkable switching delay of 17.l ps was demonstrated with 0.96 mW power dissipation per gate at 77 K using High Electron Mobility Transistors (HEMTs) [1].Since then HEMT technology has made huge impact on computers and communications and this technology was further demonstrated in supercomputers like CRAY. InGaAs, an emerging research material has a band gap of almost half of that of Silicon. A trend in the III-V band-engineering map shows that as the band gap reduces mobility increases, being highest for InSb. Higher mobility defines the speed of the VLSI ICs. However, low band gap means higher power dissipation through gate leakage and tunneling currents [2], device instability due to impact ionization and high temperature reliability issues. Simple but robust methods of increasing band gap are strain engineering and channel quantization.MBE growth and fabrication technologies help in achieving strained and scaled channels of the order of de Broglie wavelength of carriers in heterojunction transistors without compromising on the crystal quality. Scaled channels of HEMTs have shown improved logic parameters like DIBL and Sub-threshold slope [3].

EXPERIMENTAL DETAILS

The MHEMT structure consists of 500 nm-thick low-temperature (LT) InAlAs linearly graded to $In_{0.42}Al_{0.58}As$. The starting In composition was set to 0.05 to shorten the growth time. The MHEMT structure was grown on epi-ready semi-insulating (1 0 0) GaAs substrates by a solid source molecular beam epitaxy equipped with an As valved cracker. Prior to MBE growth, the substrate was heated to a surface temperature of 600°C to desorb the amorphous oxide layer. 500 nm GaAs buffer was grown at surface temperature of 585^{0}C. Then the sample was ramped down for LT-InAlAs growth. Growth rate of AlAs was 0.36 µm/h. The grade of indium content was obtained by increasing the temperature of the indium cell from 600C to about 830^{0}C to reach the In content in In_xAlAs. To generate a linearly graded buffer layer, the temperature is increased with higher rate at the beginning compared to the end of growth. The growth temperature was 380^{0}C for the LT InAlAs buffer with a V/III beam-equivalent pressure (BEP) ratio of 15. The buffer layer is lattice-mismatched with respect to the InGaAs channel and adds up controlled strain in the channel by tuning the Al mole fraction. It is therefore referred as Strain Transfer Virtual Substrate (STVS) [4].The 13.5 nm channel is sandwiched between the STVS and spacer and barrier layers of 10 nm and 6 nm respectively. The barrier is modulation doped at $n=2\times10^{18}$ cm^{-3}. The channel is maintained at a thickness below the value determined by Matthews-Blakeslee force balance critical thickness model. A streaky RHEED pattern was observed during the whole MBE growth process. The growth temperature of HT-InAlAs and HEMT was 480^{0}C. All layers in HEMT were grown with minimum As flux necessary to maintain a (2×4) RHEED pattern, which was found to give higher electron mobility for Si-doped epilayers and structures.

Vander-Pauw Hall measurements were conducted in Accent 5500 Hall System at room temperature with the magnetic field set at 0.5 T. Ohmic contacts to the samples were made by diffusing a small amount of indium through several layers at 300°C in vacuum for approximately 10 min. Crystal quality has been determined by performing HRXRD.The PL measurements were carried out using Accent Photoluminescence setup. The excitation source was the 405 nm line of a cube laser with InGaAs detector and grating of 150 g/mm. The Indium mole fractions in the layers were reconfirmed using photoluminescence.

RESULTS AND DISCUSSIONS

The measured hall mobility was 6.05e+03 $cm^2/V\text{-}s$ and sheet charge density was 1.830e+12 $/cm^2$. The lower mobility was attributed to the polar optical phonon scattering and the increase in effective mass due to strain and confinement.

The increase in the effective mass due to the electron wave function penetrating into the barrier is negligible as shown in Fig.1. It has also been reported that alloy scattering in $In_{0.53}Ga_{0.47}As$ forms about 20% of the total mobility.

Compressive strain splits the degeneracy of the light hole and the heavy hole which thereby modifies band gap. Energy correction in conduction band and valence band of InGaAs quantum well induced by strain causes a band gap shift of 0.5 eV .The channel thickness dependent energy gap is obtained by measuring the energy separation between eigen levels in the conduction band and valence band obtained from solving self-consistent coupled Schrodinger-Poisson equations for electrons and holes are solved in TCAD Silvaco [5]. The effective energy gap due to the combined effects of strain and channel quantization is calculated from the graphs. Fig. 2 shows the calculated effective energy gap for different channel thicknesses. No strain model is used as the band gap used in the simulator is strain corrected. Simulation results show that only the first energy level is filled so the electrons in the channel are purely 2DEG [6]. From photoluminescence measurements (Fig. 3) the band gap of the InGaAs QW was obtained as **0.8** eV. The bulk value of InGaAs band gap is considered as 0.751 eV. The difference in band gap has been engineered using strain and quantum confinement. The simulated values of leakage current are 1.47 mA/mm in the 13.5 nm channel HEMT.

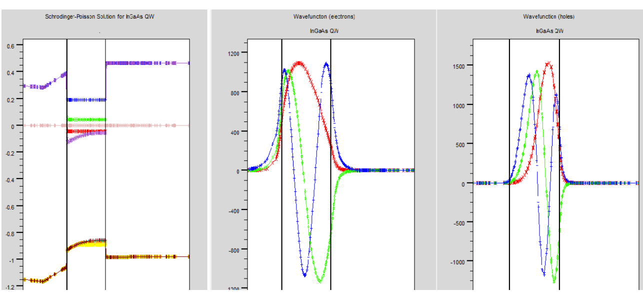

Fig.1: Self Consistent solution of schrodinger-poisson equations to determine the energy eigen values and wave functions in 13.5 nm InGaAs QW

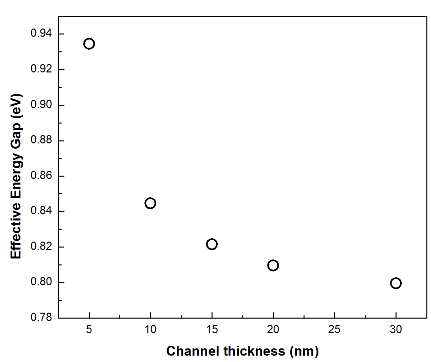

Fig 2: Dependence of effective energy gap on the dimensions of 0.76% compressively strained channel

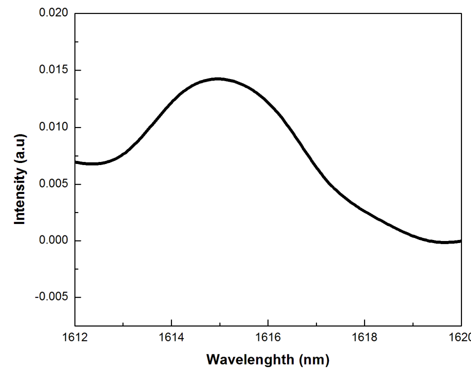

Fig 3: Photoluminescence spectra of 0.76% compressively strained 13.5 nm InGaAs QW

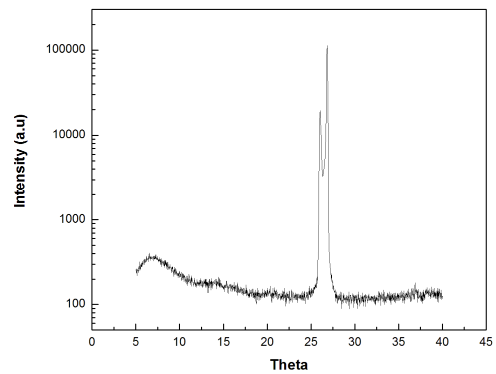

Fig 4: HRXRD to determine crystal quality

CONCLUSIONS

Further wafer level characterization will be done using Atomic Force microscopy and TEM to determine the surface roughness due to stored strain energy and interface rougness.LT PL will be conducted to determine the 2DEG in the first energy level.The quantum well structure studied will be processed for the fabrication of HEMTs for VLSI applications and their electrical characteristics studied.

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