Thermal degradation of metamorphic HEMT
InAlAs/InGaAs/InAlAs grown on GaAs substrates

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Abstract. The thermal annealing effect on electron transport properties of MHEMT nanostructures is studied for inert and atmospheric conditions. It is revealed that surface modification is mainly responsible for changes in electron properties rather than dislocation sliding and threading into active layers.

1. Introduction

Quantum well heterostructures with high electron mobility (HEMT) is most widely used material for microwave compound semiconductor electronics. Metamorphic technology provides an additional degree of freedom for heterostructure design because of flexibility of the semiconductor compound alloy composition that determines the lattice parameter. Gradual relaxation of the epitaxially grown metamorphic layers' mechanical stress allow to fit the desirable lattice parameter and thus InAs chemical composition in InAlGaAs heterosystem in metamorphic HEMTs (MHEMTs) [1,2]. The resulting advantages of MHEMT are an increase of quantum well depth, electron velocity and density, accompanied with high enough breakdown electric field and good manufacturability. Drawbacks of metamorphic HEMTs are the presence of ripple heterointerface and surface relief because of misfit dislocation array forming during the metamorphic growth [3,4]. However rather small average roughness (RMS less than 2 nm) can be achieved for that cross hatched relief by appropriate control of substrate temperature and flux ratio during the metamorphic buffer growth [5].

The best performance of the monolithic microwave integrated circuits devices based on MHEMT technology are shown for Ku, Ka and V bands for both low noise [6,7] and power applications [8,9]. Usually the best compromise between the MHEMT operation frequency and power performance leads to the choice of InAs composition ~ 35-40% in the active layers. Typical electron transport properties of MHEMTs are electron concentration in the range (2.5÷3.5) 10^{12} cm^{-2} and electron mobility in the range 8000÷9000 cm^{2}/(V·s) at room temperature for the InAs composition 35-40% [1-7]. It is well established that dislocation scattering can play important role in MHEMTs, especially in the case when threading dislocation of considerable density attains the quantum well where electrical conductivity occurs [10,11]. As the transport properties are highly sensitive to formation conditions during Molecular beam epitaxy, the comparable degradation due thermal stress in HEMT, especially power, can take place during they duti cycle. The accelerated thermal test procedures mainly involves the statistical couts of device failure [12], where the criteria of functionality fault is clear. In case of material properties degradation it isn't threshold character of degradation, so continuous dependencies
of electron transport properties on the annealing temperature and time, as well as the certain environmental conditions of annealing are important. The only known report [13] unfortunately takes into account only long-therm storage degradation of MHEMT at room temperature.

For the HEMT applications the thermal stability and performance degradation upon the thermal stress are of major importance, because they can affect the mean time to failure. Despite that wide methodology elaborated and used for the serial MMIC products, the issue of HEMT material degradation effect on MHEMT performance is still open. For the physical reasons it is very important to investigate the temperature treatment effects on the fundamental electron transport properties changes.

In this paper we have investigated the MHEMT quantum well structure electron properties changes due to thermal annealing in the different regimes.

2. Sample growth and preparation

Metamorphic In$_{0.2}$Ga$_{0.8}$As quantum well structure with linear In$_{0.15}$Al$_{0.85}$As$\rightarrow$In$_{0.40}$Al$_{0.60}$As metamorphic buffer with one side delta-Si doping was grown by molecular-beam epitaxy on semi-insulating (001) GaAs substrates without misorientation of (001) plane. Layer structure of the sample shown in Figure 1. Quantum well $L_{QW}$ has 14.5 nm width. The sample has delta doping by Si from the upper side through 5.3 nm spacer with concentration of $3.4\times10^{12}$ cm$^{-2}$. Growth temperature was 420 °C during metamorphic buffer growth, after that high temperature smoothing layer was grown at the temperature of 460 °C, accordingly to our previous study [14]. Inverse step introduced without growth interruption for the cancellation of residual strain at the top of metamorphic buffer.

For the electron transport measurements samples were processed by photolithography and mesa etching followed by the AuGe/Ni contact metallization and without an annealing. Mesa structure has van-der Pauw geometry for the simple material characterization, providing both sheet resistance and electron Hall concentration and mobility extraction without interference of specific contact resistance. I-V characteristic of all contacts showed linear performance within the range up to 20 mA. Central mesa has width of 1 mm. The sample view is presented in Figure 2.

| Layer Structure | Thickness |
|-----------------|-----------|
| i- In$_{0.37}$Ga$_{0.63}$As (cap layer) | 8 nm |
| i- In$_{0.37}$Al$_{0.63}$As (barrier) | 11 nm |
| δ-Si dopant | |
| i- In$_{0.37}$Al$_{0.63}$As (spacer) | 5.3 nm |
| In$_{0.37}$Ga$_{0.63}$As (quantum well) | 14.5 nm |
| In$_{0.37}$Al$_{0.63}$As (smoothing layer) | 180 nm |
| In$_{0.40}$Al$_{0.60}$As $\rightarrow$ In$_{0.37}$Al$_{0.63}$As (inverse step) | 48 nm |
| In$_{0.15}$Al$_{0.85}$As$\rightarrow$In$_{0.40}$Al$_{0.60}$As (metamorphic buffer with linear compositional profile) | 1180 nm |
| 5 x {Al$_{0.2}$Ga$_{0.8}$As/GaAs} (Superlattice) | {5 nm/ 3 nm} |
| GaAs (buffer) | 34 nm |
| GaAs (100) undoped substrate | |

Figure 1. Metamorphic HEMT sample layer structure design (InAs content 37% in active layers).
3. Experimental

For the temperature processing several techniques have been involved. Temporal degradation for the the moderate heating have been studied with in-situ data acquisition in atmospheric environment. Sample with the 4-contact probes on the Teflone fixture was placed on the ceramic heater with temperature stabilisation by loop controller within the accuracy of ±1 K. Magnetic field for the Hall effect measurement have been applied by automatically retracted permanent magnet. Measurement system with the commutation for the current reversal allows to exclude a thermopower voltage due to the existing temperature gradients. This setup allows to measure long therm variation of electron transport properties within the temperature range of 300 K - 550 K and durations up to $10^2$ hours.

For the heating in the inhert gase standart Modular RTP system have been adopted with permanent 4N Nitrogen blowing in the chamber during the thermal processing within the temperature range of $T_{ann}=300$ K - 550 K. For the latter techique the electron transport parameters have been measured after the certain time of annealing. For the comparison, temperature dependencies of electron concentration and mobility have been investigated in both thermal treated as-grown samples in the lattice temperature range 77 K - 300 K.

Several identical sample chips have been processed by RTP during 8 minute treatment in the temperature range of $T_{ann}=300°C÷450°C$ and measured after that.

4. Results and discussion

Long term medium temperature annealing at 250°C at ambient atmosphere gives slow resistance rise, accompanied with both mobility and concentration decrease. There is no pronounced square root law dependence, typical for diffusion processes. Sample sheet resistance change shown in Figure 3 (left). Short term high temperature annealing in contrary gives significant electron concentration decrease and respective resistance increase. Overall resistance change not exceed 0.7% within 24 hour experiment at 250°C. Providing that our mesa structures haven't additional passivation by SiO$_2$ or Si$_3$N$_4$ this result shows good stability for ambient condition accelerated oxidation. For the so small variation of resistance we can't also detect any changes in electron concentration and mobility by Hall effect.

High temperature annealing showed the changes in both electron concentration and resistance. Electron concentration drop follow square-root like character with time of annealing as shown in Figure 3 (right). Surprizingly, there weren't any detectable degradation of electron mobility. Electron transport properties were ex-sity measured at the different temperatures in the range 77 K to 300 K. All samples demonstrate the metallic behavior of the sheet resistance. Electron mobility rises while the temperature is decreased. Electron concentration measured by Hall effect, showed different behaviour - in the native sample it
slightly decreased with temperature lowering, in the annealed samples it becomes nonmonotonic. Substantial lowering of electron concentration was registered. Hall concentration is presented in Figure 4 (left) and Hall mobility (right). Thus electron concentration variation showed decrease by 10% for \( T_{\text{ann}} = 400 \) °C.

Accordingly to model [11], electron scattering by dislocation gives mobility inversely proportional to dislocation density. If dislocations is reason for electron capture, the degradation would accompanied by commensurate drop in electron mobility, but it is not the case. Another responsible mechanisms of electron concentration depletion in quantum well is change in dopant activation (self-compensation) or changes in spatial potential boundary conditions. Evolution of threading dislocation not affects narrow band channel but could give rise to the conduction band upward shift at the buffer resulting in quantum well depletion. Another possibility is change of structure surface potential due to arsenic loss in atomic scale, but it is of minor probability due to high temperature stability of InGaAs compounds.

![Figure 3. Temporal in-situ measurement of electron transport properties upon annealing temperature resistivity at \( T_{\text{ann}} = 250 \) °C (left) and concentration at \( T_{\text{ann}} = 450 \) °C (right).](image)

![Figure 4. Temperature dependence of electron Hall concentration (left) and mobility (right) of metamorphic HEMT before and after rapid thermal annealing at \( T_{\text{ann}} = 400 \) °C and 450 °C.](image)
5. Conclusion

The effect of low temperature long term and rapid high temperature annealing on the electron transport properties of metamorphic high electron mobility quantum well with 37% InAs content is presented. The structure is stable in the long term treatment at relatively small temperatures up to 250°C. The short time annealing upon Nitrogen environment at temperatures 400°C and 450 °C gives rise to specific resistance of MHEMT, mainly associated with electron concentration drop. Temporal behavior of concentration capture follow diffusion-like dependence. However, there is not accompanied drop in electron mobility, so the effect isn't connected to dislocation threading into channel. Possible mechanism can be conduction band potential pinning shift at the metamorphic buffer side. The results will be useful for conditions estimation for MHEMT transistors fabrication, especially for rapid thermal annealing of ohmic contacts.

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