Laser Assisted Molecular Beam Epitaxy (LAMBE) of Compound Semiconductor Buffer Layers and AlN, GaN Structures for High Electron Mobility Transistor

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Abstract

Rapid Thermal Processing (RTP) in the Compound Semiconductor technology has had a significant impact in making such a technology reliable and manufactureable. Since 1980, RTP has been applied to achieving control of doping profiles, achieving implant activation and the application of advanced metallization systems. Since 1990, RTP in the form of pulsed excimer laser processing has been applied to molecular beam epitaxial growth (MBE) for the development of high resistivity buffer lasers and for achieving the heterostructures necessary for high electron mobility transistors (HEMTs). The emphasis in the present paper is to review the GaAs device technology, the material problems and device structures and to show that RTP has removed key material problems which were bottlenecks in achieving a fabrication process which is reliable and high yield. The technique has been extended to nitrides and through laser assisted MBE (LAMBE), state of the art GaN and AlN layers have been grown for GaAlN based HEMTs.

1. INTRODUCTION

The basic building block for the majority of GaAs integrated circuits is the field effect transistor (FET) and its related structure, the high electron mobility transistor (HEMT). The HEMT is a modified FET in that the active channel is a triangular quantum well located at the AlGaAs/GaAs or AlGaN/GaN interface as shown in Fig 1. In such as configuration, the layer grown on top of the undoped buffer layer is n^+ and provides the electrons which will be confined at the quantum well for conduction. Conduction then occurs in an undoped layer with a minimum of impurity scattering[1,2,3].

The strategy and approach taken by university and industrial researchers in the GaAs and GaN technology has been to apply RTP (Rapid Thermal Processing) and laser annealing processes to solve or minimize the surface and interface defect problems related to these compound semiconductor materials. The results of this approach will present the application of RTP and laser processing to GaAs buffer layer and GaN, AlN heterostructure optimization. Material characterization will be correlated with device electrical performance. The material characterization will concentrate on the application of photoluminescence spectroscopy in order to examine the laser assisted MBE growth of GaAs buffer layers and hererostructures. In order to understand the effect of laser assisted growth on transport properties, lightly silicon doped GaAs layers will be investigated. Device characterization data will be shown to correlate with material performance. Likewise we will show that laser assisted MBE growth is possible for unintentionally n type GaN and AlN layers.

The initial experimental studies are based on particle emission from a GaAs surface as a result of irradiation by a focused or defocused pulsed laser beam. Some of the ways of using rapid thermal laser type processing are:

1. A pulsed laser (Nd:YAG) to heat the surface causing desorption of atoms and molecules. A second pulsed laser which will photoionize the neutral particles accumulated about the surface.
2. The use of one laser beam as a non-selective source for laser ablation of surface contaminant, and for laser ablation of compound layers from compound semiconductors.
3. The combination of 1 and 2 with MBE growth of superlattices and buffer layers in order to result in a laser processed or laser assisted MBE device structure.

The third technique has been particularly effective in optimizing device performance of both FETs and HEMTs.

2. LASER ASSISTED GROWTH BY MOLECULAR BEAM EPITAXY (LAMBE)

The objective for incorporating UV laser processing during MBE growth was to attain complete desorption of hydrocarbons from the GaAs surface and to attain cracking of the molecular beam As_4 to As_2. The surface available for MBE growth must be a perfect reconstructed 2x4 GaAs surface. The removal of hydrocarbons is necessary for attaining high resistivity buffer layers. These objectives were attained using an experimental configuration shown in Fig 1. The MBE configuration allows for both normal and glancing angle incidence. In addition, IR lamps were incorporated for rapid control of substrate temperature. Due to the effective dissorption of H, C, the low temperature (350°C) buffer layer growth became possible. LAMBE growth has been applied both to buffer layers and to the growth of superlattice donor layers. The effectiveness of laser assisted MBE growth was analyzed by mass spectrometry. The in-situ examination clearly indicates the cracking of As_4 to As^{++} by the peak at AMU 75.

The effectiveness of laser assisted MBE growth is shown by the device results attained by a laser processed superlattice high electron mobility transistor (LPHEMT). The structure is shown in Fig 2 and consisted of a laser assisted low temperature MBE buffer layer, laser formed ohmic contacts, and a delta doped superlattice donor layer. The low temperature buffer layer was attained using 60mJ/cm^2, 30ns pulses at 248nm wavelength. Thermal desorotion occurred at 580°C and 15 seconds followed by LAMBE growth. The delta doped donor layer resulted in an n^+ layer doped to $2x10^{18}cm^{-3}$, with the arsenic source shuttered during growth. A 60nm doped donor layer was attained, grown at 550°C with the laser beam at a glancing angle at 60mJ/cm^2. The ohmic contacts were AuGeNi (80wt.%, 10wt.%, 10wt.%) attained at 180mJ/cm^2, 15 pulses and 248nm wavelength.

The gate transfer characteristics were attained by measuring drain to source current (I_{DS}) as a function of gate to source voltage (V_{GS}). The presence of the 2D electron gas is shown in the gate transfer characteristics indicating a higher transconductance (Gm) at 77K in comparison with room temperature, for a unique LPHEMT.

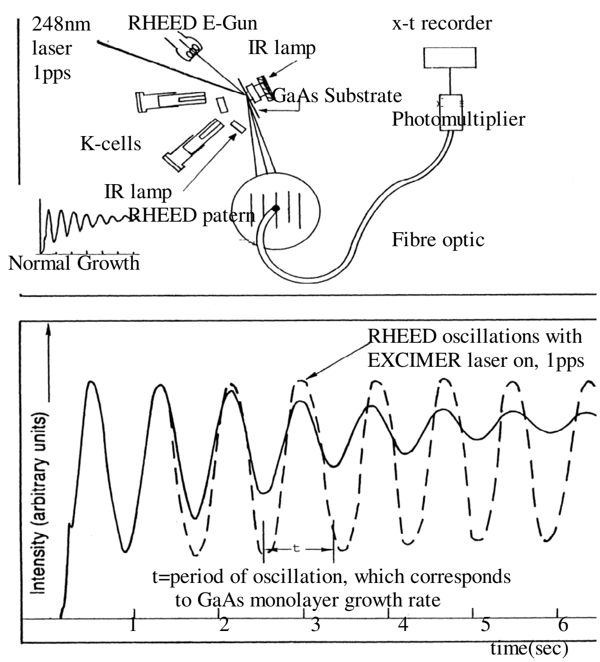
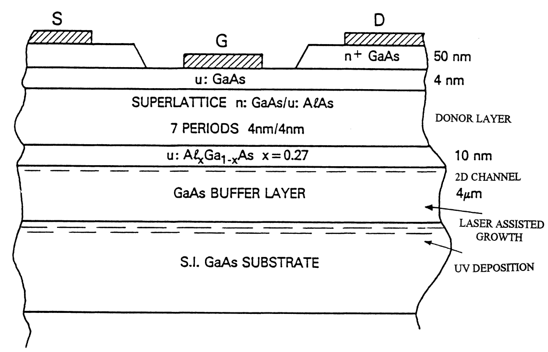


Fig 1. Pulsed Excimer Laser-MBE Growth



- Laser formed ohmic contacts
- Delta doped superlattice donor layer
- Gate length 0.75umx200um

Fig 2. Laser processing superlattice-HEMT(LPHEMT)

Table 1 Mobility u (Unit: cm^{-2}/Vsec) and Residual Doping (Unit: cm^{-3}) Measurements

Lightly Si doping GaAs layers (undesorbed)
Low level of compensation

-A-

	300K		77K	
run N	Mobility	Doping	Mobility	Doping
187V	3600	$1.2x10^{15}$	29000	$1.1x10^{15}$
197V	1500	$3.0x10^{15}$	50000	$8.25x10^{14}$
203V	7700	$9.1x10^{14}$	63000	$1.0x10^{15}$

Laser desorbed lightly Si doping GaAs layers
*Lamp desorbed layers

-B-

	300K		77K	
run N	Mobility	Doping	Mobility	Doping
238L	7700	$1.5x10^{14}$	96000	$2.7x10^{14}$
*	7400	$2.0x10^{14}$	87000	$3.0x10^{14}$

The optical properties of undoped and lightly silicon doped GaAs layers were examined by photoluminescence. The undoped layers were investigated in order to understand the incorporation of contaminants during MBE growth, while lightly silicon doped layers were investigated in order to understand their transport properties. The characteristic photoluminescence spectra for GaAs has two features of interest. The broad low energy peaks contain line broadening due to neutral donor and neutral acceptor transitions, while the narrower X peak contains excitonic transitions. Shown in Fig 3 is a typical spectrum for undoped GaAs indicating a very narrow exciton peak (3eV FWHM) characteristic of material without defects or compensating impurities.

The transport properties of undesorbed and laser desorbed GaAs layers are shown in Table 1. A significant increase in mobility has been attained through laser desorption. An effective improvement is also shown for infrared lamp desorption. The effect in both cases is due to the effective removal of hydrocarbons from the GaAs surface prior to MBE growth.

3. SUPERLATTICE HEMTS

The application of RTP through the utilization of UV lasers has added new flexibility in MBE growth. Therefore, structures such as dual channel HEMTs have benn developed. Such a structure contains a superlattice, delta or spiked doped donor layer where only the GaAs part of the superlattice is doped to $2 \times 10^{18} cm^{-3}$. The structure was grown with combined UV and IR heating where IR heating was incorporated in back of the substrate. The desorption temperature was $580^{o}C$ for 15 seconds, resulting in a reconstructed surface for MBE growth. Fig 4 shows a schematic of the substrate. The advantage of such a structure is the resultant elimination of long term transients which are present due to trapping of electrons by ionized donors in the AlGaAs. Fig 5 shows such a transient present in the drain current response of a normal HEMT. Laser processed HEMTs, on the other hand, indicate that such a transient no longer exists (Fig 5b).

Laser processing also allows a graded donor layer HEMT to be realized where the donor layer is graded from x=0.27 to zero mole fraction of aluminum. The Hall measurements from the resultant structure indicate a performance level which is optimum for such a structure. The 77K mobility was measured to be $94{,}000 cm^2/Vs$, a level which is only achieved through the improved material properties attained through laser assisted MBE growth. In summary, the rapid thermal processing combined with MBE material growth has resulted in new device structures with enhanced device performance[4,5].

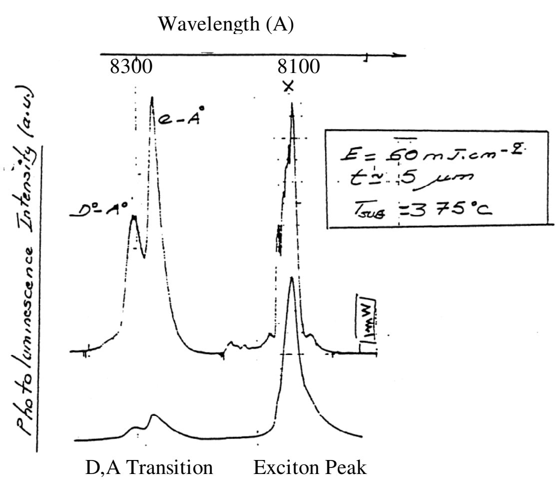


Fig 3. Undoped GaAs/GaAs MBE laser desorbed. Allows for low temperature growth

n^+ GaAs 2×10^{18}	50 nm
undoped AlGaAs	20 nm
SP GaAs/AlAs spike-doped 7 periods 4/4nm	40 nm
undoped AlGaAs	10 nm
undoped GaAs	1000 nm
(100) SI GaAs substrate	

Fig 4. Specialized dual channel HEMTs with combined UV/IR heating. $580^{o}C$/15sec; 2x1 reconstruction.

4. LAMBE GROWTH OF GAN, ALN LASERS

Laser assisted MBE growth of GaN and AlN has been achieved on GaAs by incorporating excimer laser ablation of GaN and AlN targets concurrent with Ga Knudsen cell molecular beams. The GaN ablated beam was focused broadly onto a three inch GaAs substrate, achieving lightly doped $1\text{-}3 \times 10^{17} cm^{-3}$ GaN layers. GaN ablation beam composition was achieved with a KrF_2 excimers laser and energy density measured at the target of $180 mJ/cm^2$. Likewise AlN ablation was achieved under equivalent conditions with composition modification achieved via a co-focus Al molecular beams. Hence a wide variation of GaN, AlN, and GaAlN compositions became possible to attain on laser desorbed GaAs substrate.

Field effect transistors were processed from n-GaN/GaAs and n-GaAlN/GaAs epitaxial layers. These experiments were carried out in order to show the viability of LAMBE for the development of new material structures for FETs and HEMTs. The total gate length was determined to be one micron and was defined by reactive ion etching. The source to drain distance was three microns, the measurement of the output current-voltage characteristics is performed by established means, as well as the transfer characteristics of the gate. The measured transconductance for such a structure was 120-150mS/mm, indicating predicted performance for the given geometry.

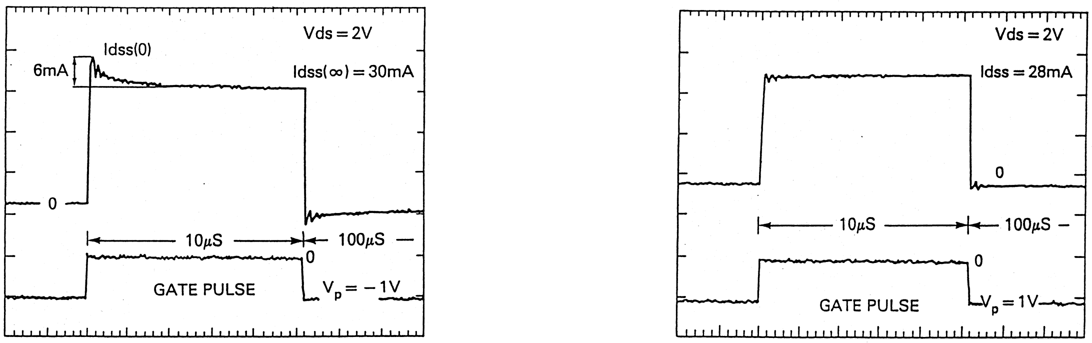


Fig 5 (a) Drain current response in normal HEFTs, and (b) Laser processed HEMTs

The GaN LAMBE growth has also been developed as a unique low temperature (600-620°C) technique based on surface chemistry of both GaAs and ZnO substrates. This technique was based on catalysis and determination of the growth kinetics so as to achieve surface cracking of ammonia and to allow for nitrogen incorporation at significantly lower temperature. Since low growth temperatures have been achieved, then ZnO substrates may be used in order to achieve better lattice matching to GaN and GaAlN. Photodissociation has been achieved with an energy density of 110-120mJ/cm^2 and has been ideal for n-type layers, but with little success for activation of p-type dopants in GaN.

5. CONCLUSIONS

The main area of pulsed thermal processing applied to the compound semiconductor technology is the incorporation of rapid thermal processing with a growth technology such as MBE. This approach has successfully been applied to the growth of HEMT structures which have resulted in state of the art performance at 12-18GHz. Optimized buffer layers and donor layers have been reported, and results have been reviewed in the present investigation.

This paper reports results of LAMBE deposited GaN, AlN and GaAlN layers on GaAs. Composition control is achieved via a concurrent Ga or Al beams. The layers achieved were n-type allowing for MESFET structures to be processed with predicted transconductance characteristics.

ACKNOWLEDGEMENTS

The authors acknowledge support from the Semiconductor Research Corporation, and from the University of Maryland Electronic Packaging Research Center. The microelectronics Research Group at the University of Crete participated in the growth of the LAMBE layers.

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