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Si and C δ-doping for device applications

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Abstract

Growth conditions have been optimised for Si and C δ-doped AlGaAs at 630°C. Very high free carrier densities up to 6×10^{18} and 3×10^{19} cm^{-3}, respectively, for Si and C δ-doped AlGaAs, were obtained. The key parameters to precisely control δ-doping concentrations were discussed. Growth of high quality Si and C δ-doped *nipi* structures, Si δ-modulation doped $In_{0.2}Ga_{0.8}As/GaAs$ quantum wells, and high performance Zn-free C δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ GRINSCH lasers were also reported. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

δ-Doping is a doping technique that attempts to spatially confine the dopants to one atomic layer during epitaxial growth of semiconductors. It is implemented using a common procedure including pre-δ-doping purge, δ-doping and post-δ-doping purge step. The doping precursor is introduced and the dopants are incorporated on the nongrowing surface during a δ-doping step. The most widely used dopants in AlGaAs grown by MOVPE are Si for n-type and Zn or C for p-type [1,2]. A high Si doping concentration usually requires a high growth temperature, while a low growth temperature is essential to achieve a high p-type doping concentration [3–7]. In this work, we optimised the growth conditions for Si and C δ-doping at 630°C. Si and C δ-doped *nipi* structures, Si δ-modulation doped $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ quantum wells, and C δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ SQW GRINSCH lasers were therefore fabricated to verify those δ-doped layers for device structures.

2. Experimental details

Si and C δ-doped AlGaAs were grown at 630°C. Precursors included TMGa, TMAl, TMIn, and

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AsH_3. The doping precursor for Si and C δ-doping were SiH_4 and TMAl, respectively. The detailed parameters used for δ-doping were given in relevant figure captions. Carrier profiles were obtained using capacitance–voltage (*C–V*) or electrochemical capacitance–voltage (EC–*V*) profiler. The sheet carrier densities were deduced by numerical integration of the carrier profile.

3. Results and discussion

SiH_4 cannot be effectively adsorbed on a nongrowing surface of AlGaAs due to its chemical stability [8], so the Si doping concentration largely depends on the partial pressure of active species like SiH_2 in the gas phase [9]. Thermal stability of molecular SiH_4 demands a high temperature for effective pyrolysis of SiH_4. In order to increase Si δ-doping concentrations at low growth temperatures, we found that the H_2 flow rate plays a very important role. At the given SiH_4 partial pressure, the optimised H_2 flow rate was about 2.5 s.l.m. under our growth conditions. At around this optimised H_2 flow rate, the sheet electron density can therefore be widely changed by simply changing the SiH_4 flow rate or δ-doping time (see Fig. 1).

C δ-doping is usually implemented using CCl_4 as the doping precursor [10]. Following our previous work, TMAl was used as a C δ-doping precursor [11]. The effective C δ-doping was conducted by introduction of a small amount of TMAl in the AsH_3-free ambient with other MO sources vented. A short δ-doping time (up to 10 s) or the time of a nongrowing surface exposing to the TMAl containing ambient retains morphology of epitaxial layers. The incomplete decomposition of TMAl ensures methyl radicals bounded to Al be co-incorporated onto a nongrowing AlGaAs surface. This led to an effective C δ-doping. We found that the free-hole density is insensitive to temperature variation over 550–630°C. The sheet hole density of C δ-doped layers can therefore be altered by the amount of TMAl introduced during the δ-doping step over the range of less than 4×10^{12} to above 8×10^{12} cm^{-2} (see Fig. 2).

A difficult structure for δ-doping is δ-doped *nipi* doping superlattices (DSs) since it requires precise control of the doping concentration and spatial confinement of the dopants. For our Si and C δ-doped layers in GaAs, the free carrier profile width is about 50 and 70 Å, respectively. Referring to the

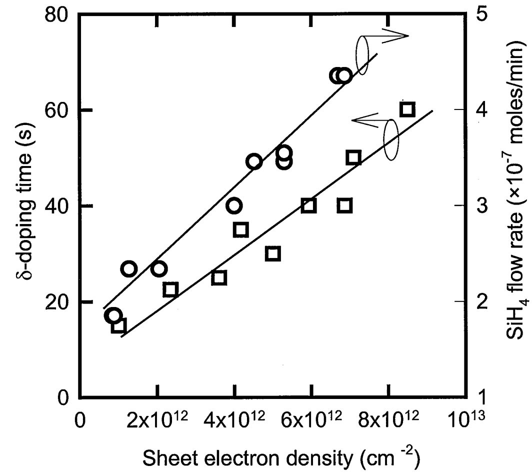

Fig. 1. Dependence of the sheet electron density of Si δ-doped layers in GaAs on SiH_4 flow rate and δ-doping time. The Si δ-doped layer was grown using 8 s pre-δ-doping purge step with an AsH_3 flow rate of 15 sccm. There was no post-δ-doping purge step. For the δ-doping time dependence, the SiH_4 partial pressure was 2 mTorr, while the δ-doping time was 30 s for the study of the SiH_4 flow rate. The H_2 flow rate during δ-doping was 2 s.l.m.

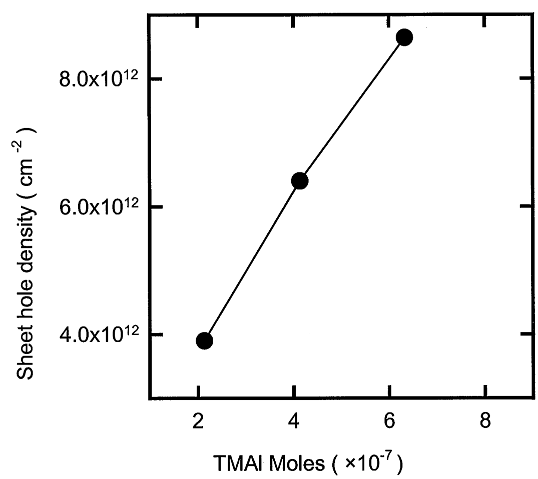

Fig. 2. Relation of the sheet hole density to the amount of TMAl introduced during the δ-doping step. The pre-δ-doping purge time was 10 s with an AsH_3 flow rate of 15 sccm. The δ-doping time was 4 s without any presence of AsH_3 followed by 4 s post-δ-doping purge step with an AsH_3 flow rate of 35 sccm.

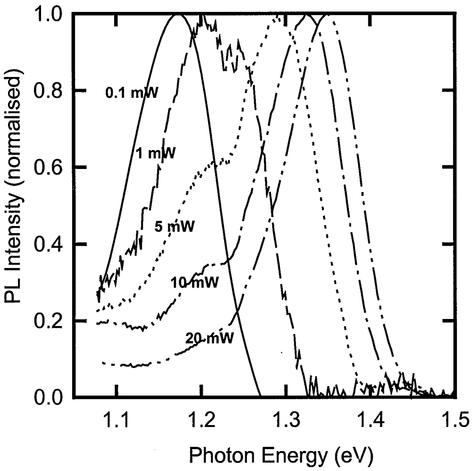

Fig. 3. Dependence of photoluminescence spectra of Si and C δ-doped *nipi* doping superlattice of GaAs on excitation intensity. The sheet carrier density of each δ-doped layer was about $3\times10^{12}\,cm^{-2}$ and the spacer layer thickness between neighbouring δ-doped layers was 150 Å.

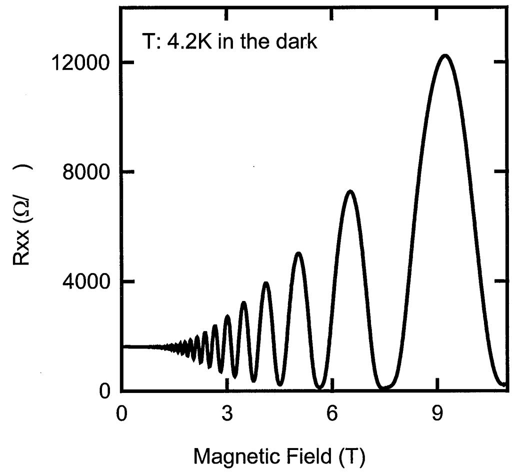

Fig. 4. The magneto-resistance as a function of magnetic fields in the dark at 4.2 K of Si δ-modulation doped GaAs/$In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW structure. The $In_{0.2}Ga_{0.8}As$ well thickness was 80 Å and the spacer layer thickness of $Al_{0.2}Ga_{0.8}As$ was 100 Å.

previous reports [2], the dopants are well confined to a few atomic layers. We used Figs. 1 and 2 to choose a right TMAl mole and a right Si δ-doping time for a given sheet carrier density of each δ-doped layer. The fully compensated Si and C δ-doped DSs with the background more than two orders of magnitude lower than the peak carrier density of δ-doped layers were successfully grown in MOVPE. The large shift of the PL peak energy (from 1.26 to 1.46 eV) as a function of excitation intensity (Fig. 3) indicates the well-established *nipi* behaviour and their comparability to other *nipi* structures grown by MBE [12].

Si δ-doping has been widely used in modulation doped AlGaAs/GaAs HEMT and InGaAs/GaAs p-HEMT structures for improved device performance [1,2]. A Si δ-doped layer forms a 2DEG in its V-shaped potential well. This deep potential well can substantially prevent the electrons from transferring into QWs, leading to undesired parallel conductance [13]. A reduced thickness of the spacer layer between two 2DEG systems (one formed in QW and the other in a Si δ-doped layer) enhances the electron transfer. On the other hand, the spread of the dopants to QW applies restriction on the use of a very thin spacer layer. Si δ-modulation doped GaAs/$In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW with a 100 Å thick $Al_{0.2}Ga_{0.8}As$ spacer layer was grown in this work. The magneto-transport measurement at 4.2 K evidences a 2DEG in QW dominates magneto-transport properties. The well-developed SdH oscillations in Fig. 4 indicate no parallel conductance in the system. This led to a very high electron density in QW of $1.11\times10^{12}\,cm^{-2}$ with a much higher Hall mobility of 44 160 $cm^2/V\,s$ [14].

In MOVPE, Zn is a widely used p-type dopant. Its fast diffusion, however, is of concern particularly for device structures requiring a post-treatment at high temperatures. C is therefore regarded as an alternative dopant owing to its lowest diffusion coefficient [15]. C δ-doped *pipi* doping superlattice (DS) was used for the ohmic contact layer in $In_{0.2}Ga_{0.8}As$/GaAs GRINSCH laser structure. We found that the average hole-density of the C δ-doped DS grown using the TMAl mole of 4×10^{-7} (see Fig. 2) is $>1\times10^{19}\,cm^{-3}$ with the Hall mobility of about 20 $cm^2/V\,s$. Using the standard photolithography technique, the measured room temperature light–current characteristics of an edge emitting ridge waveguide laser diode under CW operation is illustrated in Fig. 5. The threshold current density, as determined using the as cleaved

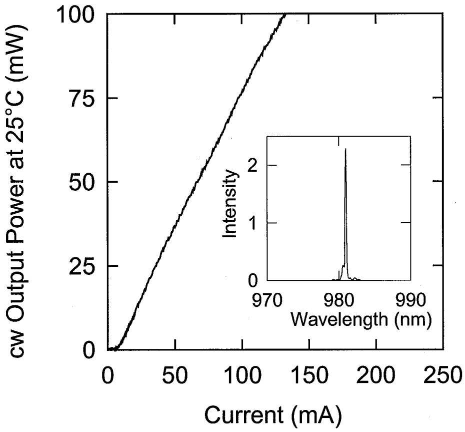

Fig. 5. The measured room temperature light–current characteristics of an edge emitting ridge waveguide GRINSCH $In_{0.2}Ga_{0.8}As/GaAs$ SQW laser diode. The single mode spectral output at 981 nm is shown in the inset, which was measured at 1.4× threshold current in the pulsed mode (1% duty cycle).

100 μm stripe laser bars, was about 80 A/cm^2. This is comparable to other 980 nm lasers fabricated using bulk-doped ohmic layers [16,17].

4. Conclusions

Si and C δ-doped layers in AlGaAs have been grown at 630°C. Free carrier densities obtainable by simply changing one controllable growth parameter cover the most interesting ranges for device applications. The control of δ-doping concentrations as well as well-spatial confinement of the dopants in those δ-doped layers ensure fabrication of high quality device structures like Si and C δ-doped *nipi* doping superlattices, Si δ-modulation doped $GaAs/In_{0.2}Ga_{0.8}As/AlGaAs$ QWs and Zn-free $In_{0.2}Ga_{0.8}As/GaAs$ GRINSCH lasers.

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