HIGH PURITY AlGaAs GROWN BY MOLECULAR BEAM EPITAXY

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Abstract - **We report the growth and photoluminescence study of very high quality $Al_xGa_{1-x}As$ layers grown by molecular beam epitaxy over the $0 \leq x \leq 0.38$ composition range. Heterostructure doped-channel FET's (DCFET's) manufactured using pseudomorphic AlGaAs/InGaAs/GaAs heterostructures containing such a layer have produced an output power of about 1 W/mm with 7.8 dB small signal gain and 60 % power-added efficiency at 18 GHz.**

I. INTRODUCTION

The problems of growth and study of the ternary semiconductor $Al_xGa_{1-x}As$ attract attention of investigators because of the importance of this material for the fabrication of optoelectronic and microwave devices [1]. The growth of the high purity material is especially important for the high frequency power field effect transistor fabrication. The power of these devices increases with the gate breakdown voltage (V_B). The value of V_B depends on the electric breakdown strength of the AlGaAs layer which lie under the transistor gate. It is obvious that the lower the concentration of the background impurities and defects in the layer, the higher the breakdown strength of the material.

In this paper we report on the growth and photoluminescence study of high quality $Al_xGa_{1-x}As$ layers with AlAs fraction in the range of $0 \leq x \leq 0.38$. The low concentration of background impurities in these layers is confirmed by the following data: (i) the linewidths of the exciton line in the PL spectra of these layers do not exceed the theoretically predicted values and are the lowest ever reported for $Al_xGa_{1-x}As$ layers with AlAs fraction x in the same range; (ii) the ratio of the intensities of the free exciton to shallow impurity-related lines is very high and equals 300–1000, depending on the layer. The material has been used in AlGaAs/InGaAs/GaAs heterostructures for doped-channel field effect transistors (DCFET's).

II. EXPERIMENT

Epitaxial layers and AlGaAs/InGaAs/GaAs heterostructures were grown on semi-insulating (100)-oriented GaAs substrates in a Riber-32P MBE system with a three-inch substrate holder. As the initial materials, we used 8N purity Ga produced by the Institute of Microelectronics Technology and High Purity Materials of Russian Academy of Sciences, 6N purity Al produced by Vacuum Metallurgical, and 7N purity As produced by Furukawa. The MBE system was baked at a temperature of 200°C for 2 weeks. After cooling the chamber and filling the cryoshrouds with liquid nitrogen the residual pressure less than 10^{-11} Torr was achieved under idle temperatures of effusion cells. It was shown recently that the main sources of background impurities in MBE grown GaAs layers are substrate heater and initial materials loaded into the cells, especially arsenic [2,3]. Therefore special attention and time have been given to outgassing the cells and the substrate heater. The Ga and Al cells were outgassed for several hours at temperatures that exceeded by 150°C the temperatures used during growths, and the As cell was outgassed at an As beam equivalent pressure of $5 \cdot 10^{-5}$ Torr. The pretreating of the MBE system guaranteed the production of two-dimensional electron gas structures with electron mobility at liquid helium temperature greater than $10^6\ cm^2 \cdot V^{-1} \cdot s^{-1}$. The thicknesses of the investigated GaAs and $Al_xGa_{1-x}As$ layers were 2.5 μm. The layers were separated from the substrate by a GaAs buffer layer with a thickness of 0.2 μm. A short-period superlattice of twenty pairs of $(AlAs)_5(GaAs)_2$ was grown in the middle of the buffer layer. In order to decrease the rates of surface and interface recombination the layers were sandwiched between thin (25 nm) AlAs layers. The growth temperature was 630°C. The arsenic pressure was kept sufficient to maintain the (3x1)As superstructure stabilization of the growth surface. To obtain the free carrier concentration Van der Pauw measurements were performed at room temperature with Hall factor taken to be unity. All the layers demonstrated p-type conductivity. The concentration of holes showed a decrease from $8 \cdot 10^{14}$ cm^{-3} in the GaAs layer to $(1\text{-}5) \cdot 10^{14}$ cm^{-3} in the $Al_xGa_{1-x}As$ layers. Stationary PL was analyzed through a 0.6 m double grating monochromator, detected with a cooled photomultiplier tube with S-20 photocathode and recorded using a photon counting system. The radiation of an Ar^+-laser (488 nm) was used to excite PL. The excitation power density was changed from $3 \cdot 10^{-4}$ to 160 W·cm^{-2} using neutral density filters. The PL spectra were corrected for the wavelength-dependent sensitivity of the system, which was determined through black-body-radiation measurements. The AlAs fraction in the $Al_xGa_{1-x}As$ layers was determined using relation determined by Allali et al [4]:

$$E_g(AlGaAs) = E_g(GaAs) + 1.447x - 0.15x^2, \qquad (1)$$

where the alloy band gap value E_g(AlGaAs) was calculated by adding the free-exciton binding energy as a function of AlAs fraction [5] to the energy position of the free exciton line.

A cross section of AlGaAs/InGaAs/GaAs pseudomorphic heterostructures containing high purity $Al_xGa_{1-x}As$ layers is shown in Table 1.

TABLE I

Layers	thickness
n^+ GaAs (Si:$6x10^{18}$cm^{-3})	40 nm
i GaAs	5 nm
i-$Al_{0.38}Ga_{0.62}As$	30 nm
n^+ $In_{0.15}Ga_{0.85}As$ (Si: $2.8x10^{18}$ cm^{-3})	15 nm
i GaAs	10 nm
i-$Al_{0.38}Ga_{0.62}As$	100 nm
i GaAs	100 nm
SL $(AlAs)_5\,(GaAs)_{10}$ x 20	
i GaAs	300 nm
GaAs (100) substrate	400 µm

DCFET's with 0.5-µm gate length and 180-µm gate width have been fabricated using these heterostructures.

III. EXPERIMENTAL RESULTS

Figure 1 shows 4.2 K PL spectra of GaAs and $Al_xGa_{1-x}As$ layers with different alloy compositions. The line of the free-exciton transition (FX) at 1.5151 eV energy dominates in the spectrum of the GaAs layer [6]. The line of band-to-acceptor (e,A) recombination due to carbon acceptors is also present in the spectrum, its intensity being smaller than the intensity of FX line by a

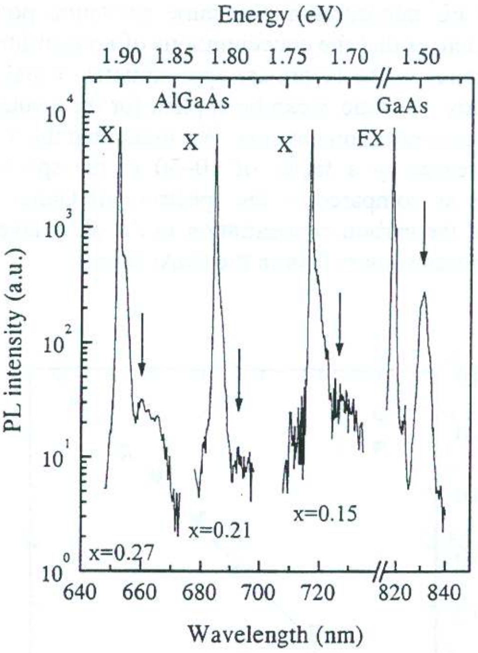

Fig.1 Low-temperature (T=4.2K) photoluminescence spectra of GaAs and $Al_xGa_{1-x}As$ layers measured at an excitation density of 30 mW/cm^2. The arrows mark energy positions of the band to acceptor transitions.

factor 30. An asymmetrical line marked X with energy position depending on AlAs fraction dominates in the spectra of $Al_xGa_{1-x}As$ layers. The faint (e,A) line is also present in the spectra. The intensity of this line is lower than that of the X line by a factor of 300–1000, depending on the sample. The low-energy tail of the X line is described by a Lorenzian function and does not change with a temperature (T) increase from 4.2 to 30 K, while the high-energy tail is approximated by a temperature-dependent exponential function $f(\hbar\omega)=a \cdot \exp(-\hbar\omega/kT)$, where a is a constant, $\hbar\omega$ is photon energy, and k is the Boltzman's constant. The shape of the X line and its temperature dependence and low concentration of impurity evidences that this line is associated with the recombination of free excitons [7].

In order to compare the concentrations of carbon in the GaAs and $Al_xGa_{1-x}As$ layers we calculated the ratio (S) of the integrated intensity of (e,A) line to the integrated intensity of X line. In general, this ratio can not be considered as a tool for reliable comparison of the acceptor concentration because the intensities of exciton and acceptor-related lines depend differently on nonequilibrium charge carrier concentration. Moreover, usually the probability of carrier capture by an impurity in an alloy depends on the alloy composition following the change of the impurity ionization energy. However, in $Al_xGa_{1-x}As$ the carbon acceptor ionization energy is a slow function of AlAs fraction in the range x=0–0.3; besides, all the investigated layers have shown almost the same integrated PL intensities at the same excitation powers, which evidences that the concentrations of nonequilibrium charge carriers in the layers are approximately equal, and consequently, the ratio S can be applied for the evaluation of carbon concentration changes. We found that the S ratio value decreases by a factor of 10–30 in the spectra of $Al_xGa_{1-x}As$ as compared to the spectrum of GaAs. This means that the carbon concentration in the alloy layers is at least ten times lower than in the GaAs layer.

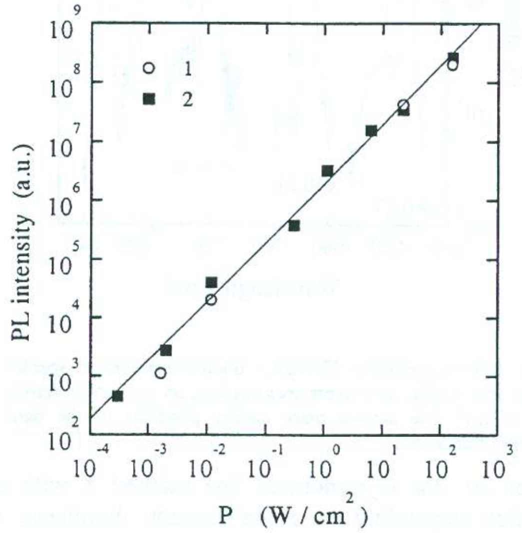

Fig. 2 Integrated intensity of the X line in the layers with AlAs fractions of (1) x=0.15 and (2) x=0.21 as a function of excitation power density (P). The solid line is a linear fit of experimental data.

The dependencies of the integrated intensity of X line on the excitation power density for the layers with AlAs fraction of x=0.15 and x=0.21 are shown in Fig.2. The dependencies are linear in a wide power density range from $3\cdot10^{-4}$ to $160\ W\cdot cm^{-2}$. The linear behavior of the dependencies evidences that excitonic recombination is the dominating channel of nonequilibrium charge carrier recombination in the investigated layers, and the concentration of centers of nonradiative recombination is very low. It was found recently [1,8] that oxygen impurity and point lattice defects are the main nonradiative recombination centers in $Al_xGa_{1-x}As$, so we may conclude that the concentrations of these impurity and defects are low in the investigated layers.

Figure 3 shows the linewidth of the X line as a function of AlAs fraction in the alloy, measured at an excitation power density of $30\ mW/cm^2$. The lowest experimental values of the excitonic linewidths in samples grown by MBE and metalorganic vapor phase epitaxy reported in the literature [9,10] as well as the values calculated by Lee

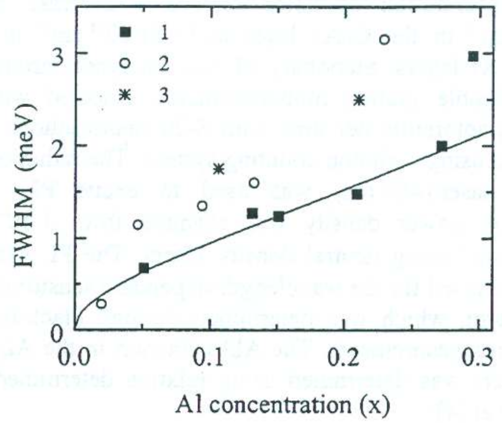

Fig. 3 Experimental values of the linewidths of the free exciton line as a function of AlAs fraction x. The experimental points are: (1) current work, (2) taken from [9], and (3) from [10], respectively. The x values for the data from [9] and [10] were recalculated using the expression (1). The solid line is the theoretical curve calculated by Lee and Bajaj [11].

and Bajaj for perfectly random alloys [11] are also shown in this figure for comparison. The authors of the Ref.9 and Ref.10 have also determined the Al fraction value x from the energy position of the free exciton line, however for calculation of the x value they applied the Casey's relation $E_g(AlGaAs) = E_g(GaAs)+1.247\cdot x$ [12], which differs from the relation (1) used in the present work. In order to compare our results with the data of papers [9] and [10] we recalculate their x values using the expression (1). One can see that the values of the exciton linewidth observed in this study are by 30–50 % lower than the previous experimental data, and in the spectra of the most pure layers with the AlAs fraction x=0.15 and x=0.21 the linewidths equal to 1.24 meV and 1.48 meV, respectively. An excellent agreement between the experimental and calculated data is observed, therefore from the data shown in this figure one can conclude that the main mechanism of the exciton line broadening in our samples is alloy disorder while broadening due to ionized impurities can be neglected.

We suppose that the extremely low concentration of the background impurities in the investigated $Al_xGa_{1-x}As$ layers is the result of the specific surface reconstruction used during growth. In order to verify this assumption we grew a layer of AlGaAs at the (2x4)As surface reconstruction which is usually used for the fabrication of GaAs and AlGaAs layers. Figure 4 shows the PL spectra of the layers with AlAs fraction x=0.15 grown at surface reconstruction (3x1)As and (2x4)As.

One can see that the band to impurity line dominated in spectrum of the latter layer, its total PL intensity being

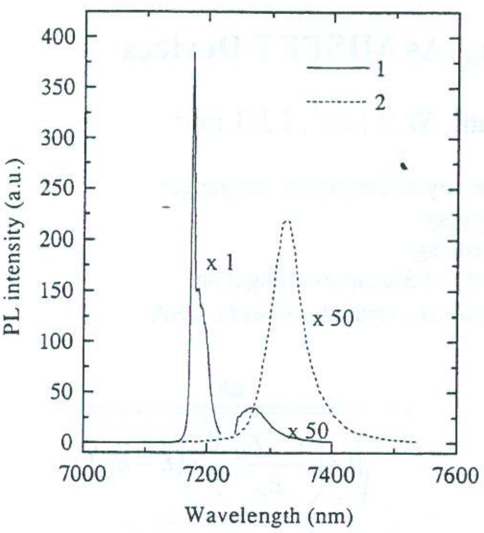

Fig.4 Low-temperature (T=4.2K) photoluminescence spectra of $Al_xGa_{1-x}As$ layers grown at surface reconstructions (3x1)As - (1) and (2x4)As - (2).

more than two order of the magnitude lower than the intensity of the layer grown at the (3x1)As surface reconstruction. Therefore, the data of Fig.4 confirm our assumption. A possible reason for the low impurity concentration in the $Al_xGa_{1-x}As$ layers is the impurity segregation on the growth surface. It is well established that carbon and oxygen impurities segregate on the direct GaAs/AlGaAs interface [8,13,14]. We believe that the expulsion of the impurities from the layers is especially efficient in the layers grown at the surface reconstruction (3x1)As, however further investigation is required for clarification of the effect of surface reconstruction on the impurity segregation.

DCFET's have been fabricated using AlGaAs/InGaAs/GaAs pseudomorphic heterostructures containing high purity $Al_xGa_{1-x}As$ layers. The gate breakdown voltage (V_B) of the device reached 25 V, while that of the devices fabricated using a similar heterostructure containing silicon-doped $Al_xGa_{1-x}As$ layer with electron concentration of $n=1\cdot10^{16}$ cm^{-3} was equal to 18 V. The DCFET's have demonstrated an output power of about 1 W/mm with 7.8 dB small signal gain and 60 % power-added efficiency at 18 GHz.

IV. CONCLUSIONS

In conclusion, we have described the high-quality MBE-grown $Al_xGa_{1-x}As$ layers with very low concentration of background impurities. The use of these layers in AlGaAs/InGaAs/GaAs pseudomorphic heterostructures for doped-channel field effect transistors allowed the fabrication of devices with an output power of about 1 W/mm and 7.8 dB small signal gain at 18 GHz.

The authors would like to thank Dr. A.M. Gilinsky and Dr. N.T. Moshegov for useful discussions.

V. REFERENCES

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