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High density 2DEG in $A^{III}B^{V}$-semiconductor heterostructures and high electron mobility transistors on their basis

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Situation in high electron mobility transistor (HEMT) technology is discussed. Nowadays N-AlGaAs/InGaAs/GaAs pseudomorphic HEMT's are considered as most advanced for mm-wave monolithic circuits, but metamorphic N-$\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}/\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ HEMT's grown on GaAs substrates are very promising for the future high frequency devices. High density 2DEG in HEMT's is analysed by means of Hall effect and photoluminescence measurements. Processing technology of the sub-0.25 μm pseudomorphic HEMT's, metamorphic HEMT's and their characteristics are also described.

High electron mobility transistor (HEMT) technology is widely used for high frequency application due to the enhanced electron mobility (μ_{2D}) and velocity (v_{st}) at high electron density (n_{2D}) in a device channel. This provides high values of the device current I_D, transconductance $g_m = dI_D/dV_G$, cutoff frequency $f_\tau = v_{st}/2\pi L_g$, output gain G and the low value of noise. Main tendensies of evolution of this technology correspond to investigation of heterostructures with higher values of the conduction band offset ΔE_c and, respectively, n_{2D}, with higher values of the energy seperation $\Delta E_{\Gamma L}$ between Γ and L valleys, with lower electron effective mass m_e and, respectively, with higher values of μ_{2D} and v_{st}, combined with the reduction of the HEMT gate-length L_g.

Since 1980 HEMT technology has passed the following stages:

– lattice matched (LM) N-AlGaAs/InGaAs/GaAs HEMT's with $\Delta E_c \simeq 250\,\mathrm{meV}$ and maximum electron density $n_{2D}^{\max} < 1 \cdot 10^{12}\,\mathrm{cm}^{-2}$;

– pseudomorphic (PM) N-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}/\mathrm{GaAs}$ HEMT's [1] which provide higher ΔE_c ($\Delta E_c \simeq 300\,\mathrm{meV}$) and $n_{2D} \simeq 2 \cdot 10^{12}\,\mathrm{cm}^{-2}$; however, effect of strain relaxation restricts the maximum values of In content y and thickness d_{ch} of $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}$ channel layer by critical values, and, respectively, restricts the values of n_{2D}, μ_{2D} and v_{st};

– the highest frequency is realized in InP-based LM-$\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}/\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ HEMT's [2]: $\Delta E_c > 500\,\mathrm{meV}$, $n_{2D} > 3.5 \cdot 10^{12}\,\mathrm{cm}^{-2}$ and $\mu_{2D} > 10\,000\,\mathrm{cm}^2/\mathrm{V \cdot s}$ at 300 K; there are some disadvantages associated with a rather low value of the Schottky barrier heigth for $\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}$ and with impact ionization in $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ channel due to rather small energy band-gap $E_g \simeq 750\,\mathrm{meV}$;

– recent advantages of HEMT technology are associated with the metamorphic (MM) N-$\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}/\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}/\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ HEMT-structures with desirable In contents y, x, ranging from 0 to 0.60, grown on the lattice mismatched GaAs substrate [3]; they provide $\Delta E_c > 600\,\mathrm{meV}$, $n_{2D} > 4 \cdot 10^{12}\,\mathrm{cm}^{-2}$ and $\mu_{2D} > 10\,000\,\mathrm{cm}^2/\mathrm{V \cdot s}$ at 300 K.

This paper is devoted to the investigation of the high density 2DEG in N-AlGaAs/InGaAs/GaAs and N-InAlAs/InGaAs/InAlAs MM-structures and HEMT's on their basis, because former, nowadays, is the most advanced industrial technology for mm-wave monolithic circuits and latest is very promising for the future high frequency electronics.

Molecular beam epitaxy of HEMT-structures

HEMT-structures studied here were grown by molecular beam epitaxy (MBE) on (001) GaAs substrates. PM-HEMT-structure consists of an 0.3 μm GaAs buffer layer, an undoped InGaAs channel layer ($d_{ch} < 25\,\mathrm{nm}$), an undoped AlGaAs spacer layer (thickness $d_s < 10\,\mathrm{nm}$), a δ (Si)-doped layer, undoped 20 nm AlGaAs Schottky layer and a Si-doped n^+-GaAs ($3 \cdot 10^{18}\,\mathrm{cm}^{-3}$) cap layer. The quality of the AlGaAs/InGaAs interface and maximum values $\mu_{2D}^{\max}$ and $n_{2D}^{\max}$ for 2DEG are essentially limited by the surface segregation of In atoms during MBE growth. Removing these atoms by means of the growth interruption and subsequent surface heating allows to achieve μ_{2D} as high as $53\,000\,\mathrm{cm}^2/\mathrm{V \cdot s}$ at 77 K.

Typical MM-HEMT-structure consists of an undoped 0.3 μm GaAs buffer layer, an undoped 1.3 μm AlInGaAs relaxed buffer layer (RBL) with changeable composition from GaAs to $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$, an undoped 0.3 μm $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ layer, a short period superlattice, an undoped $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}$ channel layer, an undoped $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ spacer layer ($d_s < 10\,\mathrm{nm}$), a δ (Si)-doped layer, an undoped 20 nm $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ Schottky layer and a 40 nm n^+-$\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{As}$ ($5 \cdot 10^{8}\,\mathrm{cm}^{-3}$) cap layer. RBL is of main importance in MM-HEMT's. It is inserted between substrate and active layers to accommodate large lattice mismatch by formation of dislocations, to trap them, and to prevent their propagation in HEMT-structure. Samples with different RBL composition and depth profile have been grown. The highest electron mobility was achieved in the samples with the RBL depth profile corresponding to the nearly constant value of the gradient of the lattice mismatch.

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They nave $\mu_{2D} = 32\,000\,\mathrm{cm^2/V{\cdot}s}$ and $n_{2D} = 2.2\cdot10^{12}\,\mathrm{cm^{-2}}$ at $T = 77\,\mathrm{K}$, a good surface morphology (associated with the cross match pattern) and a large photoluminescence (PL) signal.

Transport properties and photoluminescence spectra of HEMT-structures

In order to understand, how the variations of InAs mole fraction y and thickness of the channel layer d_{ch} influence on the characteristics of 2DEG in N-Al$_x$Ga$_{1-x}$As/In$_y$Ga$_{1-y}$As/GaAs heterostructures, including the influence of the backside heterobarrier, and also to answer the question how is 2DEG redistributed under variation of thickness d_{ch}, Hall measurements of μ_{2D} and n_{2D} and photoluminescence studies of PM-HEMT-structures have been performed. It was shown that μ_{2D} practically does not depend on d_{ch} in the range from 19 to 3 nm. According to PL studies, the regular spatial redistribution of 2DEG between InGaAs and GaAs layers occurs, when d_{ch} is reduced. At $d_{\mathrm{ch}} > 10\,\mathrm{nm}$ 2DEG is mainly located in InGaAs. However, at $d_{\mathrm{ch}} < 7 \div 8\,\mathrm{nm}$ more electrons transfer from InGaAs to GaAs, and at $d_{\mathrm{ch}} < 3.5 \div 4\,\mathrm{nm}$ practically all the electrons transfer to GaAs. Because μ_{2D} is approximately so high in GaAs as in InGaAs, the electron mobility may be independent on d_{ch}, as observed experimentally. At the same time, these results demonstrate that electron scattering associated with the backside heterobarrier (effect of wich should increase with reduction of d_{ch}) has not any visible impact on μ_{2D}. This finding is in contrast with $\mu_{2D}\,(d_{\mathrm{ch}})$ dependence for AlGaAs/GaAs/AlGaAs system, where the reduction of d_{ch} below 30 nm results in a strong degradation of μ_{2D} due to the enhanced influence of the backside interface. To clear the role of the backside heterobarrier in the electron scattering, PM-HEMT-structures with AlGaAs layer as a backside heterobarrier also have been studied. It has been found that replacement of GaAs by AlGaAs leads to a significant reduction of μ_{2D} (about 4 times) and n_{2D}, and to their more strong reduction with decreasing d_{ch}. The cause of this, along with the increased interface electron scattering, can be associated with the more and more penetration of electron wave functions into AlGaAs barrier (due to quantum-mechanical tunneling). So, more and more time electrons will spend in AlGaAs, where their mobility is extremely low.

PL spectra of MM-In$_x$Al$_{1-x}$As/In$_y$Ga$_{1-y}$As/InGaAs heterostructures with $x, y = 0.32$ and 0.52 also have been studied. At $d_{\mathrm{ch}} > 40\,\mathrm{nm}$ these spectra correspond to the bulk material and two PL lines correspond to respective band-gaps E_g. The band-gap discontinuities ΔE_g at the interfaces are 0.70 and 0.72 eV for x, y of 32 and 52%, respectively. For $d_{\mathrm{ch}} < 30\,\mathrm{nm}$ the InGaAs "bulk" PL line in each sample is split up into two components, associated with the optical transitions between the two lowest 2DEG subbands and the hole subband. It should be noted that the PL lines in MM-HEMT-structures are more weak and broader than those in PM-HEMT-structures, evidently due to the higher dislocation density.

Sub-quarter-micrometer PM-HEMT's and MM-HEMT's

The realization of HEMT's with the gate length $L_g < 0.25\,\mu\mathrm{m}$ was performed by using the electron lithography in combination with the special mask consisted of a SiO$_2$ layer, a metallic layer and an electron resist layer. After the exposure and the development of the electron resist, the very narrow opening was formed in the metallic layer by Ar$^+$-ion beam etching. Such metallic mask allows to realize $L_g < 0.2\,\mu\mathrm{m}$ and to avoid the problem of the low stability of the electron resist to the plasma etching.

In PM-HEMT the typical extrinsic transconductance g_m^{ex} was ranged from 300 to 550 mS/mm, the drain current density I_D was in the range: $300 \div 500\,\mathrm{mA/mm}$. In MM-HEMT's the best results have been obtained for In content of 0.32. Their main advantages over PM-HEMT's are associated with the higher values of g_m^{ex} and I_D: g_m^{ex} was ranged from 500 to 800 mS/mm, and I_D from 500 to 900 mA/mm, which are explained by larger n_{2D} and v_{st} in MM-HEMT's. In the case of PM-HEMT's, rf characteristics in the frequency range $f = 12 \div 37\,\mathrm{GHz}$ have also been studied. The presence of the strong correlation between output gain G and g_m^{ex} was confirmed at 12 GHz. It was shown that the dependence of G on the gate width W_g at 37 GHz has a maximum at $W_g = 120\,\mu\mathrm{m}$, but for 12 GHz G increases with W_g up to $150\,\mu\mathrm{m}$ without any maximum. The increase of G in the range $40 \div 100\,\mu\mathrm{m}$ for $f = 37\,\mathrm{GHz}$, and up to $150\,\mu\mathrm{m}$ for $f = 12\,\mathrm{GHz}$ are explained by increase of the absolute transconductance. The reduction of G at $W_g > 120\,\mu\mathrm{m}$ for $f = 37\,\mathrm{GHz}$ is a result of mismatch of the PM-HEMT parameters with the input of the measurement wave guide line in the mm-wave range. At $f = 12\,\mathrm{GHz}$ such mismatch is expected at $W_g > 150\,\mu\mathrm{m}$.

References

[1] L.D. Nguyen, P.J. Tasker, D.C. Radulescu, L.F. Eastman. IEEE Trans. El. Dev., **36**, 2243 (1989).

[2] L.D. Nguyen, L.E. Larson, U.K. Mishra. Proc. IEEE, **80**, 491 (1992).

[3] P. Win, Y. Druelle, A. Cappy. Appl. Phys. Lett., **61**, 922 (1992).

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