High-Field Electron Drift Velocity in InGaAs Quantum Wells

K. Požela[*1], J. Požela[2], V. Jucienė[3]

Semiconductor Physics Institute, Center for Physical Sciences and Technology / Vilnius 01108, Lithuania

[*1]kpozela@pfi.lt; [2]pozela@pfi.lt; [3]juciene@pfi.lt

Abstract- **The electric field dependences of electron mobility and drift velocity in InGaAs quantum wells (QWs) of modulation doped $Al_xIn_{1-x}As/In_yGa_{1-y}As$ and $Al_xGa_{1-x}As/In_yGa_{1-y}As$ heterostructures are reviewed. It was theoretically predicted and experimentally observed that the enhancement of the low-field mobility in the $Al_xIn_{1-x}As/In_yGa_{1-y}As$ QW up to 1.2×10^4 cm^2/(V s) can be achieved by increasing the In fraction *y* in the QW and barriers up to *y* = 0.7–0.8 and by decreasing Al fraction *x* up to *x* = 0.2 in the barrier layer. The largest increase by a factor of 1.8 in the electron mobility and maximal drift velocity up to (2–4)$\times10^7$ cm/s was achieved by inserting the InAs phonon wall into the InGaAs QW. The InAs phonon wall is a new type of a specific barrier transparent to electrons and reflected phonons. The created heterojunctions with high electron mobility and drift velocity were proposed and tested as basic elements for high-speed electronic devices in the 0.5–1.0 THz frequency range.**

Keywords- Heterostructures; AlInAs/InGaAs; AlGaAs/InGaAs; Microwave and THz Electronics; High-Field Electron Drift Velocity in QWs; Electron–Phonon Scattering in QWs

I. INTRODUCTION

Semiconductor heterostructures have become the basic elements of contemporary semiconductor electronics. In particular, modulation-doped AlGaAs/GaAs, AlInAs/InGaAs and AlGaAs/InGaAs heterostructures are important for application in high electron mobility transistors (HEMTs), which are the basic elements for high-speed devices in microwave and terahertz (THz) frequency ranges [1-10].

In a modulation-doped structure, the spatial separation of free electrons from an impurity-doped layer reduces impurity scattering; however, it enhances electron scattering by interface (IF) phonons in thin quantum wells (QWs).

In this paper, the possibilities of enhancing the electron mobility and drift velocity saturated in high electric fields by reducing scattering of electrons by phonons are examined. Hot electron transport peculiarities in the modulation doped AlGaAs/InGaAs and AlInAs/InGaAs heterostructures are reviewed.

The following effective tools for enhancing the electron mobility and high-field drift velocity in InGaAs QWs are proposed: (1) confinement both phonons and electrons in the QW of HEMT channel; (2) decrease of electron–IF phonon interaction strength by choosing a composition of semiconductors in the heterostructures; and (3) insertion of a phonon wall (specific barrier transparent to electrons and reflected phonons) into the QW. Application of these advanced methods allows us to create heterostructures – basic elements of high-speed electronic devices for the new area of semiconductor electronics in the 0.5–1.0 THz frequency range.

II. SATURATED ELECTRON DRIFT VELOCITY IN HIGH ELECTRIC FIELDS IN AlGaAs/InGaAs AND AlInAs/InGaAs QANTUM WELLS

Saturation of electron drift velocity in high electric fields in basic semiconductors (Si, GaAs, InGaAs and others) limits the enhancement of main parameters of field effect transistors: the maximum cutoff frequency and gain.

Fig. 1 shows the typical electric field dependences of electron drift velocity, $v_{dr}(E)$, in bulk GaAs and InAs, as well as in $In_{0.2}Ga_{0.8}As$ and $In_{0.5}Ga_{0.5}As$ alloys. One can see that the drift velocity in bulk $In_yGa_{1-y}As$ alloys are saturated in higher electric fields at 1×10^7 cm/s in spite of a large increase in low-field mobility and maximal drift velocity $v_{max}(E_{th})$ at the threshold field E_{th} as a mole fraction *y* of In increases in the $In_yGa_{1-y}As$. It should be noted that $E_{th}\approx4$ kV/cm and weakly depends on the composition of $In_yGa_{1-y}As$.

Fig. 2 shows the experimentally measured field dependences of electron drift velocity in the GaAs QW, which radically differ from the similar dependences in the bulk GaAs. The region with a negative differential conductivity is absent. The drift velocity in GaAs QWs in high electric fields exceeds the saturated drift velocity in bulk materials, in spite of much less low-field mobility in GaAs QWs in comparison with bulk materials [11-15]. In samples A and B with a thicker QW (30 nm), the drift velocity exceeds the saturated drift velocity in the bulk GaAs by a factor of 1.5–2. The largest increase of the drift velocity is observed experimentally in sample B. This structure contains three thin (1 monolayer of InAs) polar optical (PO) phonon barriers dividing the GaAs QW into four thin phonon wells. At *E* = 15 kV/cm, the drift velocity in sample B reaches 2.1×10^7 cm/s.

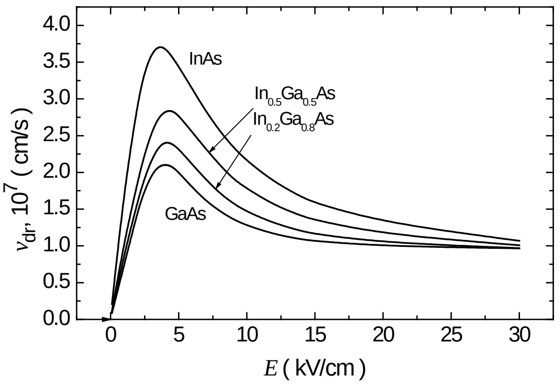

Fig. 1 Field dependences of drift velocity of electrons in the bulk $In_yGa_{1-y}As$ solid solution at y=0, 0.2, 0.5, and 1

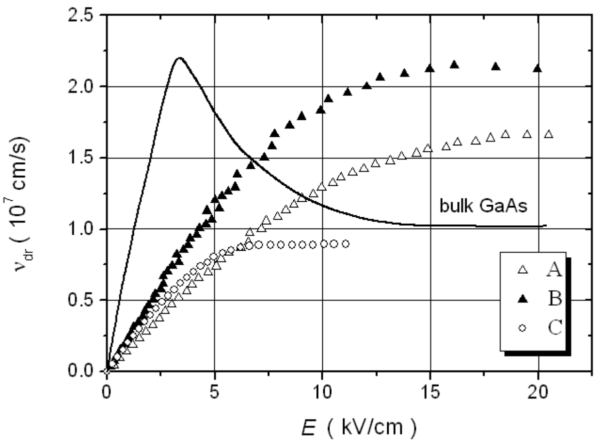

Fig. 2 Field dependences of the electron drift velocity $v_{dr}(E)$ in the double-barrier $Al_{0.3}Ga_{0.7}As/GaAs/Al_{0.3}Ga_{0.7}As$ structures with a different thickness of the GaAs QW: 30 nm in samples A and B and10 nm in sample C. Sample B has three thin (1 monolayer of InAs) phonon barriers inserted into the GaAs layer. The full curve represents $v_{dr}(E)$ in the bulk GaAs

However, in sample C with the thin QW (10 nm), the drift velocity at electric fields E > 6 kV/cm saturates and does not exceed the velocity in the bulk GaAs. This is explained by a strong increase of electron scattering rate (SR) by IF phonons in the thin (<10 nm) QW [16].

The field dependences of the electron drift velocity $v_{dr}(E)$ in the QWs calculated using Monte Carlo simulations at various fractions of Al in the QW barriers for the $Al_xIn_{1-x}As/In_{0.5}Ga_{0.5}As/Al_xIn_{1-x}As$ structure are shown in Fig. 3(a) [17, 18]. The $v_{dr}(E)$ in the QWs was calculated taking into account the scattering of electrons only by PO and IF phonons confined in the QW. The $In_{0.5}Ga_{0.5}As$ QW thickness is accepted as 16 nm.

The field dependences of the occupancy of Γ and L valleys in the QWs of the corresponding compositions are shown in Fig. 3(b).

The most essential feature of the $v_{dr}(E)$ in the $Al_xIn_{1-x}As/In_{0.5}Ga_{0.5}As$ QW is the effect of the QW barrier composition on the threshold field for the intervalley transfer, E_{th}, in the QW layer. The threshold field E_{th} (at which the drift velocity in the $In_{0.5}Ga_{0.5}As$ QW is maximal) increases and the low-field mobility decreases as the x fraction of Al in the barrier layer increases.

The intervalley Γ–L transfer is responsible for the decrease of the drift velocity at $E>E_{th}$ (see Fig. 3(b)). One can see that the mobility in the sample with x = 0.2 becomes less than that with x = 0.5 at $E > 7$ kV/cm. Then, at $E > 7$ kV/cm, the drift velocity in the sample with x = 0.5 becomes greater than that with x = 0.2.

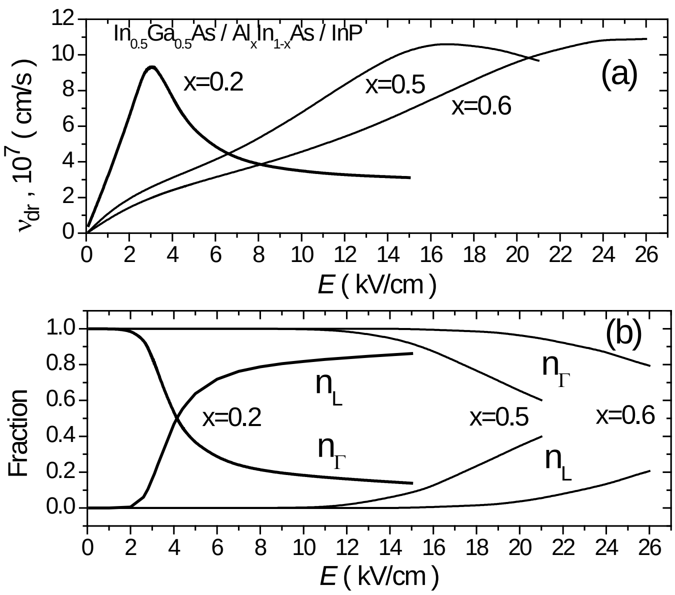

Fig. 3 Calculated field dependences of (a) drift velocity of electrons and (b) fractions of electrons n_{Γ}/n_s and n_L/n_s in Γ and L valleys, respectively, in $In_{0.5}Ga_{0.5}As$, for various compositions of the $Al_xIn_{1-x}As$ barrier layer: x=0.2, 0.5, and 0.6

Therefore, the decrease of the fraction x of Al up to x = 0.2 in the QW barrier layers are the effective tool for enhancing the low-field electron mobility in the modulation doped $In_yGa_{1-y}As/Al_xIn_{1-x}As$ heterostructures.

The experimental field dependences of the InGaAs QW channel conductivity at different QW barrier compositions are presented in Fig. 4. The measurements were performed on the samples in the form of gateless mesa 100-μm-wide structures with deposited 100×100 μm^2 Au/Ni/Ge ohmic contacts onto the samples. The length of the samples (a distance between ohmic contacts) was d = 10 μm. The voltage pulses of 80 ns duration were used.

One can see that the current-field dependences are sub-linear. The threshold field E_{th} for current saturation and instabilities depends on the QW barrier composition and changes from 2 to 7 kV/cm. Note that the E_{th}=2.5 kV/cm is significantly less than that E_{th} =4 kV/cm in bulk materials.

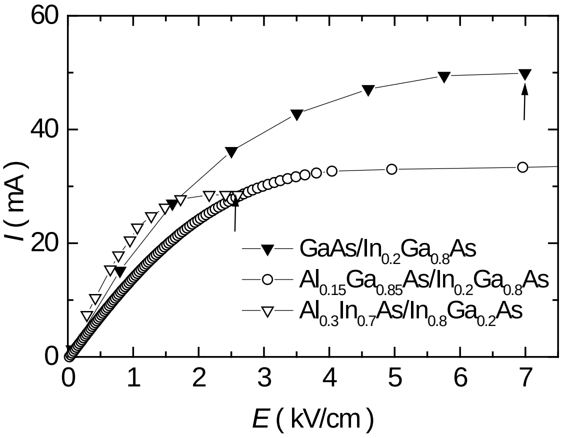

Fig. 4 Field dependences of the current in the InGaAs QW channel for various types of QW barrier layers. Arrows show the threshold field of current instabilities

Therefore, the experimental data confirm the predicted excess of the electron drift velocity in the moderately thick GaAs QW over the maximum saturated drift velocity in a bulk GaAs.

III. ENHANCEMENT OF ELECTRON MOBILITY IN InGaAs QANTUM WELLS BY CHANGING COMPOSITION OF $Al_xIn_{1-x}As/In_yGa_{1-y}As$ AND $Al_xGa_{1-x}As/In_yGa_{1-y}As$ HETEROSTRUCTURES

Let us consider the possibilities to increase the electron mobility and high-field drift velocity in the modulation doped AlInAs/InGaAs and AlGaAs/InGaAs QW channels by tuning the electron scattering by IF phonons by choosing the composition of barriers in $Al_xIn_{1-x}As/In_yGa_{1-y}As$ and $Al_xGa_{1-x}As/In_yGa_{1-y}As$ heterostructures.

Electron–IF phonon scattering in $Al_xIn_{1-x}As/In_yGa_{1-y}As$ heterostructures has been investigated in [11, 17–22]. A scattering rate of an electron (with the initial state wave vector $\mathbf{k}_i$) by ν-mode PO and IF phonons confined in the QW of thickness L_n can be estimated as [11]:

$$W_\nu(k_i, L_n) = WO\int_0^{2\pi}\left|\int_{-L_n/2}^{+L_n/2}\varphi_{ei}\ \varphi_{q\nu}\ \varphi_{ef}\,dz\right|^2 F_\nu^2\,d\theta, \tag{1}$$

where φ_{ei} and φ_{ef} are the initial and final normalized electron wave functions; $\varphi_{q\nu}$ is the phonon potential envelope function; $F_\nu{}^2$ is the factor determined by the interaction force of electrons with PO and IF phonons; and $WO = me^2/(\pi\hbar^3)(N_{q\nu} \pm 1/2 + 1/2)$, where m and e are the electron mass and charge, respectively, $N_{q\nu}$ is the ν- mode phonon number, and $\hbar$ is the Planck's constant.

According to the dielectric continuum model, the factor F_ν^2 for confined PO phonons with the frequency ω_L is equal to

$$F_{PO}^2 = \frac{\hbar\omega_L}{2}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_{st}}\right), \tag{2}$$

and for confined IF phonons with frequency ω_{IF},

$$F_{IF}^2(\omega_{IF}) = \left[\varepsilon'\int_{-L_A/2}^{L_A/2}\left(q^2\varphi_q^2 + \varphi_q'^2\right)dz\right]^{-1} \quad \text{with} \quad \varepsilon' = \frac{2\omega_{IF}\left(\omega_L^2 - \omega_T^2\right)}{\left(\omega_{IF}^2 - \omega_T^2\right)^2}, \tag{3}$$

where χ_∞ and χ_{st} are the optical and static dielectric constants, respectively, ω_L and ω_T are the longitudinal and transverse optical phonon frequencies, respectively [19].

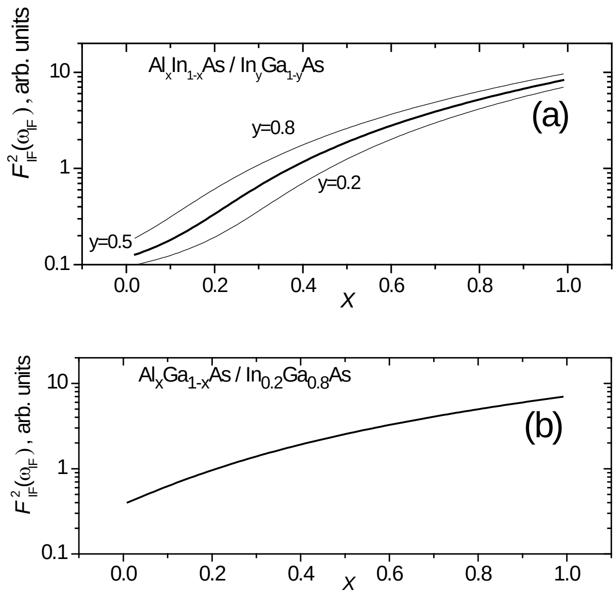

Fig. 5 Dependences of the interaction force of electrons with IF phonons with the frequency ω_{IF}, $F^2_{IF}(\omega_{IF})$, on fractions x of Al in the composition of barriers and y of In in the composition of the QW for the (a) $Al_xIn_{1-x}As/In_yGa_{1-y}As$ and (b) $Al_xGa_{1-x}As/In_{0.2}Ga_{0.8}As$ heterostructures

The frequency ω_{IF} and, therefore, the factor $F^2_{IF}(\omega_{IF})$ are determined by the composition of semiconductors forming the interface. The dependence of the factor $F^2_{IF}(\omega_{IF})$ on the fraction x of Al in the $Al_xIn_{1-x}As$ barrier for several values of the fraction y of In in the $In_yGa_{1-y}As$ QW is shown in Fig. 5(a). It can be seen that the factor $F^2_{IF}(\omega_{IF})$ increases as the fraction x of Al in the $Al_xIn_{1-x}As$ and $Al_xGa_{1-x}As$ barriers increases. The variation in the fraction x of Al in the barrier allows us to vary the electron SR by confined IF phonons in QWs by a factor of tens. The smaller value of $F^2_{IF}(\omega_{IF})$ corresponds to the larger value of the electron mobility. In the $Al_xIn_{1-x}As/In_{0.5}Ga_{0.5}As$ structure, the factor $F^2_{IF}(\omega_{IF})$ at x=0.5 is seven times larger in comparison with that at x=0.2. Accordingly, the calculated low-field electron mobility at x=0.2 is three times larger in comparison with that at x=0.6 (see Fig. 3).

In the $Al_xGa_{1-x}As/In_{0.2}Ga_{0.8}As$ structure, the factor $F^2_{IF}(\omega_{IF})$ at x=0.15 is two times large than that at x=0 (see Fig. 5(b)). The experimentally measured drift velocity for the $GaAs/In_{0.2}Ga_{0.8}As$ structures exceeds this value for the $Al_{0.15}Ga_{0.85}As/In_{0.2}Ga_{0.8}As$ structures by a factor of 1.3 (see Fig. 4).

The increase in the electron mobility as the electron–IF phonon SR decreases was experimentally observed for four types of heterostructures: $Al_{0.15}In_{0.85}As/In_{0.2}Ga_{0.8}As$, $GaAs/In_{0.2}Ga_{0.8}As$, and $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ and $Al_{0.3}In_{0.7}As/In_{0.8}Ga_{0.2}As$ (Table 1).

TABLE 1 HALL MOBILITY μ_H AND SHEET ELECTRON DENSITY n_{s0} AT 300 K IN THE SAMPLES WITH DIFFERENT In AND Al FRACTIONS IN THE QW AND BARRIERS

Heterostructures	**μ_H, 10^3 $cm^2V^{-1}s^{-1}$**	**n_{s0}, 10^{12} cm^{-2}**
$Al_{0.3}In_{0.7}As/In_{0.8}Ga_{0.2}As$ (HEM)	12.3	1.4
$Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$	6.2	1.0
$GaAs/In_{0.2}Ga_{0.8}As$	6.4	2.0
$Al_{0.15}Ga_{0.85}As/In_{0.2}Ga_{0.8}As$	5.0	2.9

The experimental measurements of electron Hall mobility in the grown novel $Al_{0.3}In_{0.7}As/In_{0.8}Ga_{0.2}As$ and the conventional modulation doped $Al_{0.48}In_{0.52}$ $As/In_{0.53}Ga_{0.47}As$ heterostructures confirm this large increase in the electron mobility with the increased InAs content in the barrier and QW layers. The measured electron mobility and sheet electron density in the conventional modulation doped $Al_{0.48}In_{0.52}$ $As/In_{0.53}Ga_{0.47}As$ structures were $\mu_H = 6.2\times10^3$ $cm^2V^{-1}s^{-1}$ and $n_{s0} = 1.0\times10^{12}$ cm^{-2} at room temperature. Meanwhile, in the novel $Al_{0.3}In_{0.7}As/In_{0.8}Ga_{0.2}As$ structures (named as high electron mobility (HEM) structure), μ_H and n_{s0} reach the values of 12.3×10^3 $cm^2V^{-1}s^{-1}$ and 1.4×10^{12} cm^{-2}, respectively. It is worth to note that at 77 K, the electron mobility and density in HEM structures were $\mu_H = 50.5\times10^3$ $cm^2V^{-1}s^{-1}$ and $n_{s0} = 1.3\times10^{12}$ cm^{-2} [20, 24].

Thus, for the first time, the largest increase in the electron mobility in the modulation-doped AlGaAs/InGaAs and AlInAs/InGaAs QWs is obtained by choosing the composition of the both AlGaAs and AlInAs barriers and InGaAs QW layers. It should be noted that the mobility value of 12.3×10^3 $cm^2V^{-1}s^{-1}$ achieved in the $Al_{0.3}In_{0.7}As/In_{0.8}Ga_{0.2}As$ structure is among the best ones ever reported for AlInAs/InGaAs heterostructures (μ =(10–16)$\times10^3$ $cm^2V^{-1}s^{-1}$) at 300 K [25–27].

Therefore, the increase of fraction y of In in the QW up to y =0.7–0.8 as well as the decrease of fraction x of Al to x=0.2 in the barrier layer are the effective tool for enhancing the electron mobility in the modulation doped $Al_xIn_{1-x}As/In_yGa_{1-y}As$ heterostructure.

IV. HIGH-ELECTRIC FIELD ELECTRON TRANSPORT IN AlInAs/InGaAs QUANTUM WELLS WITH INSERTED InAs BARRIERS (PHONON WALLS)

We will consider a thin layer of InAs as a deep and thin QW in the centre of the thick (17 nm) AlInAs/InGaAs QW. It is assumed that the InAs layer does not disturb an electron wave function in AlInAs/InGaAs QW, but reflects PO and IF phonons. InAs layer is a barrier for phonons – phonon wall.

PO and IF phonon confinement in narrow phonon layers by inserting a thin InAs layer (phonon wall) into a QW of modulation doped AlInAs / InGaAs heterostructures is used to decrease the electron–phonon scattering rate and increase the electron mobility [7, 20–24].

Let us find the optimal InAs layer thickness to achieve the largest increase of low field electron mobility in the $In_{0.5}Ga_{0.5}As$.

Fig. 6 shows the calculated dependence of mean electron mobility in the $In_{0.5}Ga_{0.5}As$ QW on a thickness L_A of the InAs layer inserted into the QW centre. The mean electron mobility in the QW is estimated as

$$\overline{\mu}(L_A) = \frac{e}{\overline{m}(L_A)}\frac{1}{WL(L_A)}, \quad (4)$$

where m is the mean electron effective mass in the layered heterostructure and $WL(L_A)$ is the total scattering rate WL of electrons with the energy of 50 meV by confined PO and IF phonons in the 17 nm-thick InGaAs QW. One can see the alternating change of the mobility in the QW dependently on the InAs insert thickness.

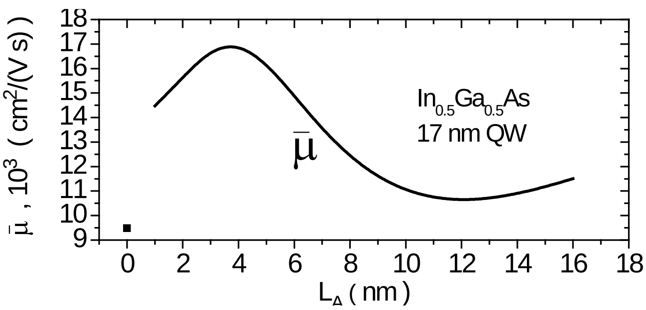

Fig. 6 Estimated dependences of the mean mobility $\overline{\mu}$ of electrons having the energy of 50 meV on the thickness L_A of the inserted InAs layer into the 17-nm $In_{0.5}Ga_{0.5}As$ QW. The black dot shows the mobility in the $In_{0.5}Ga_{0.5}As$ QW in the absence of the InAs layer

The competition between the SR increase and the effective mass decrease determines the alternating dependence of the mobility on the inserted InAs layer thickness L_A. At $L_A > 5$ nm, the electron mobility decreases because of an increase in the electron–phonon SR in the InAs layer in spite of the increase in electron population with lower effective mass in the wider InAs layer. One can see that the mean electron mobility $\overline{\mu}$ increases to the maximal value at L_A = 4 nm, and it exceeds the mobility in the structures without the InAs insert by a factor of 1.8.

Five types of the modulation doped double barrier $In_{0.5}Al_{0.5}As/In_{0.5}Ga_{0.5}As/In_{0.5}Al_{0.5}As$ heterostructures with the InAs layer of different thickness inserted into the center of 17-nm-thick InGaAs QW were grown using molecular beam epitaxy. The structures were grown on InP substrates.

Table 2 shows the experimental data of low-field mobility and density of electrons in the samples of $Al_{0.5}In_{0.5}$ As/$In_{0.5}Ga_{0.5}$As/ $Al_{0.5}In_{0.5}$ As heterostructures with the InAs layer of different thickness inserted into the center of 17-nm-thick InGaAs QW.

It should be noted that the Hall electron mobility μ_H and density n_{sH} measured in the grown heterostructures differ from μ_{sB} and n_{sB} measured from geometrical magnetoresistance in the samples with deposited ohmic contacts. These facts are explained in [1] as a result of the change of HEMT channel conductivity due to change of the field perpendicular to the QW channel plane when the ohmic contacts are deposited.

TABLE 2 MAXIMAL DRIFT VELOCITY, THRESHOLD FIELD, ELECTRON MOBILITIES AND DENSITIES IN THE SAMPLES $Al_{0.5}In_{0.5}As/In_{0.5}Ga_{0.5}As$ WITH InAs INSERTS

Sample No. $In_{0.5}Ga_{0.5}As$ (17-nm QW)	Thickness of InAs inserts, nm	μ_H, 10^3 $cm^2/(V \cdot s)$	n_{sH}, 10^{12} cm^{-2}	μ_{sB}, 10^3 $cm^2/(V \cdot s)$	n_{sB}, 10^{12} cm^{-2}	v_{max}, 10^7 cm/s	E_{th}, 10^3 V/cm
861	–	8.39	2.61	3.48	0.84	1.0	12
864	3.5+3.5	1.34	2.7	1.7	1.04	2.2	17
865	4.0	9.78	3.24	11.5	1.3	2.0	3
867	4.0	9.11	2.85	9.06	1.22	2.0	5
868	4.0	3.06	3.96	4.0	2.67	2.0	7

The low-field mobility μ in samples 865 and 867 with the inserted 4-nm InAs layer reaches 10^4 $cm^2/(V\ s)$ and is much higher than that in the basic sample 861 without the InAs insert. The mobility in sample 864 with the thicker (3.5 + 3.5 nm) InAs layer in the InGaAs QW is the lowest. This is in agreement with the estimation of the mobility dependence on the inserted InAs layer thickness L_A (see Fig. 6). The inserted 4-nm InAs layer in sample 868 is highly doped, while the InAs inserts in samples 865 and 867 and in all other samples are not doped. The low-field mobility in sample 868 due to high electron scattering by charged impurities is much lower than those in samples 865 and 867.

The electric field dependences of the conductivity of the InGaAs QW with the inserted InAs layer were measured on the samples in the form of gateless mesa-structures (400 μm in width) with a deposited line of Au/Ni/Ge ohmic contacts having an area of 400×400 μm^2 and spaced by distance d = 18 μm.

The field dependences of the drift velocity, $v_{dr}(E)$, are shown in Fig. 7. In high electric fields, the maximal drift velocity v_{max} at the threshold field E_{th} for the electron inter-valley transfer in the samples with the InAs inserts is around 2×10^7 cm/s. For sample 861 without the InAs insert, the maximal drift velocity is 1×10^7 cm/s. It is worth noting that the threshold field E_{th} in samples with the lower mobility is much larger than those in high-mobility samples 865, 867. This means that the maximal drift velocity v_{max} in the samples with lower electron mobility μ is achieved at higher threshold electric fields E_{th}. This is in agreement with the $v_{dr}(E)$ calculations (see Fig. 3).

It is worth noting that the drift velocity in the fields of 1–4 kV/cm in the samples 865 and 867 with the inserted 4-nm InAs phonon wall in the 17-nm $In_{0.5}Ga_{0.5}As$ QW exceeds the drift velocity in the sample 861 without the inserted 4-nm InAs phonon wall 2–5 times.

Therefore, the insertion of the InAs phonon wall into the InGaAs QW is the most effective tool for the enhancement of the electron mobility and drift velocity in InGaAs QWs.

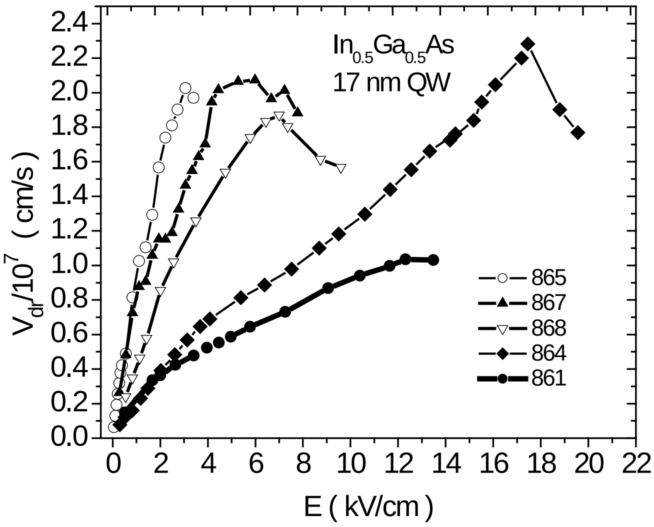

Fig. 7 Experimental field dependences of the drift velocity, $v_{dr}(E)$, in different types of heterostructures (see Table 2)

V. CONCLUSIONS

Therefore, the theoretical and experimental investigations of electric field dependence of drift velocity in the InGaAs QW discover the following peculiarities of electron transport at high electric fields in the InGaAs channel of high-speed transistors.

- The confinement and localization of PO and IF phonons as well as electrons in QWs with thickness of 10–30 nm decrease the electron–phonon scattering rate.
- The electron–IF phonon SRs are regulated by the composition of the $Al_xIn_{1-x}As/In_yGa_{1-y}As$ heterostructures.
- The InAs layer inserted into the InGaAs QW is a new type of barrier – a phonon wall transparent to electrons and reflected PO and IF phonons – effectively enhances the electron mobility and drift velocity in the InGaAs QWs.

The effective tools for the great enhancement of the electron mobility and drift velocity in the InGaAs QW were proposed and realize

- The engineering of the electron–phonon interaction strength by increasing the In fraction y in the $In_yGa_{1-y}As$ QW up to y= 0.7–0.8 and by decreasing Al fraction x up to x = 0.2 in the $Al_xGa_{1-x}As$ barrier layer; and
- The insertion of the InAs phonon wall into the QW. When the 4 nm-InAs layer is inserted into the 17-nm thick InGaAs QW, the mobility reaches 10^4 $cm^2V^{-1}s^{-1}$ and exceeds the mobility in the structure without the InAs insert by a factor of 1.8.

The realization of these tools allows us to obtain the mobility in the InGaAs/AlInAs up to 10^4 $cm^2V^{-1}s^{-1}$ and the maximal drift velocity in high electric fields up to (2–3)×107 cm/s. The created heterojunctions with the high electron mobility and drift velocity were proposed and tested as basic elements for high-speed electronic devices in the 0.5–1.0 THz frequency range.

It is worth noting that InGaAs/AlInAs heterostructures with a lower scattering rate and higher mobility and maximal drift velocity were produced. The transistors having $f_T >$ 300 GHz were made on a basis of these heterostructures in Institute of Ultrahigh Frequency Semiconductor Electronics of Russian Academy of Sciences (Moscow) [28].

ACKNOWLEDGMENT

This research was partially supported by the Research Council of Lithuania.

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Karolis Požela was born in Vilnius, Lithuania in 1960. He is graduated from the Physics department of Vilnius University in 1983. In 1991 he received the doctor degree from Vilnius University in natural sciences.

He joined the Semiconductor Physics Institute (Vilnius, Lithuania) in 1982 as a laboratory assistant, junior research associate (1983-1991), research associate (1991-1997), from 1997 (till the present time) as a senior research associate. In 2000 he worked as a research assistance at the Dept. of Physics and Astronomy of Glasgow University (Scotland, UK). Scholarships at Manchester University, Great Britain (1990), Parma University, Italy (1992-1994 and 1996-1997), University of Illinois, Urbana, USA (1998), Chalmers university, Gothenburg, Sweden (1999). The main field of interest is semiconductor physics and technology, microwave electronics, high speed electronics, non-linear effects in quantum wells, computer simulation, biomaterials for medical restoration, ionizing particle light emitting detectors, international project preparation and implementation. He published more than 100 papers in these fields. Dr. K.Požela is awarded by the Lithuanian Science Prize in 2006.

Juras Požela graduated from the Physics department of Moscow University in 1952. In 1956 he received the degree of candidate of sciences from Leningrad University in 1956 and Doctor degree in physics from Ioffe Physicotechnical Institute in 1964.

From 1956 he joined the Physics and Math. Institute of Lithuanian Academy of Sciences (LAS), as researcher, head of laboratory and director, from 1967 he was a director Semiconductor Physics Institute of LAS (till 1984). He held the positions in the LAS as vice-president (1972-84) and president (1984-92). In 1992-96 he was Member of Parliament (Seimas) of Lithuanian Republic. From 1997-till the present time he is a Principal Researcher at Semiconductor Physics Institute. The main field of interest is semiconductor physics and technology, informatics and computer technology, high-speed electronics. He is an author of books: J. Požela, “Physics of High-Speed Transistors”, (Plenum, 1993); J. Pozhela, “Plasma and Current Instability in Semiconductors”, (Pergamon, 1981), and co-author of nine books and over than 300 scientific articles. He reported at international conferences and scientific meetings at many countries all over the world.

Prof. J. Požela is Full Member of Lithuanian Acad. Sci. (1968), Full Member of Russian Acad. Sci. (1984), Member of European Acad. Sci and Arts (1991), and of Acad. Europaea (1993).

Vida Jucienė was born in Lithuania. She was graduated from the Physics Department of Vilnius University in 1960. In 1975 she received doctoral degree from Vilnius University in physics.

From 1960 she joined the Physics and Mathematics Institute of Lithuanian Academy of Sciences, and from 1967 – the Semiconductor Physics Institute as a junior researcher. From 1985 up to now she worked as senior research associate at the same institute. Scholarship was at Ioffe Physicotechnical Institute. The main field of interest is semiconductor physics and technology, non-linear effects in quantum wells, X-ray detectors. She is an author of over than 100 scientific articles and two books on physics of high-speed transistors.