HIGH FREQUENCY DEVICES AND HIGH SPEED INTEGRATED CIRCUITS TECHNOLOGY, BASED ON THE A_3B_5-SEMICONDUCTOR COMPOUNDS, IN THE REPUBLICS OF THE FORMER USSR

(Invited paper)

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ABSTRACT

The present paper is devoted to a brief analysis of the present state and the prospects for the future of technology of the high frequency devices and high speed integrated circuits based on the A_3B_5-semiconductor compounds, including the A_3B_5-heterostructures, in the republics of the former USSR.

INTRODUCTION

In USSR, as in the other countries, A_3B_5 microelectronics has been actively developed since the 1970's and it covered the two main directions: the analog high frequency devices and the high speed digital integrated circuits. Interest to this technology is connected to some advantages of the A_3B_5-compounds over the silicon. They are associated with the higher values of the electron mobility μ_e and electron velocity v_D and, respectively, with the higher values of the frequency and the speed of operation of the devices and integrated circuits, and with the lower value of their power consumption. A_3B_5-devices also have the higher value of the radiative hardness. This technology is also very promosing for optical (LED, lasers, optical modulators, photodetectors, solar batteries) and optoelectronic devices and IC, since the A_3B_5 compounds have the "direct" energy gap and, respectively, very high optical efficiency, and in this case the effective combination of the optical and electronic devices at the single chip is realized. The A_3B_5-nanostructures are also very effective for the new nanoelectronic devices based on the effect of the size quantization of the electron spectrum. In A_3B_5-compounds these effects are expressed much more strongly than in Si, due to the smaller value of the electron effective mass m_e^*. As the main components of the high performance analog and digital A_3B_5-devices, the MESFET's, the HEMT's (High Electron Mobility Transistors), the Schottky diodes, p-i-n-diodes, Gunn-diodes and the resonant tunneling quantum well-structures were widely used.

A_3B_5 HIGH FREQUENCY ANALOG DEVICES (HFAD)

During the last 20 years A_3B_5 - HFAD technology has passed the way from the GaAs-MESFET and the different types of GaAs-diodes, based on the n-doped epitaxial layers, grown by LPE (liquid phase epitaxy) and MOCVD (metal organic chemical vapor deposition) to the High Electron Mobility Transistors (HEMT's) based on the pseudomorphic N-AlGaAs/InGaAs/GaAs heterostructure quantum wells and the metamorphic N-InAlAs/InGaAs/InAlAs heterostructures on the mismatched GaAs substrates, grown by molecular beam epitaxy (MBE). The successful development of the epitaxial growth technology has provided the increase of the values of μ_e, v_D and the electron density n_{2D} in the device channel, the reduction of the gate-channel distance and the thickness of the electron channel layer. It was accompanied by the improvement of the device processing technology (the lithography, the dry etching technique and other operations): the gate length of FET's L_g was reduced from 1.5-2.0 μm (in 1980) untill 0.13-0.25 μm at the present time. As a result, the device characteristics were essentially improved: the frequency of operation of MESFET's was reached 60 GHz.

The modern sub-quarter-micro-meter-pseudomorphic - HEMT technology, developed in IRE RAS [1,2], is based on the combination of the precise electron beam lithography with the special multi-layer mask system formed by the ion-beam- and plasma-chemical etching. This processing technology has the principal advantages over the widely used bi-layer- or three-layer-electron resist technology and provides the higher reproducibity of the sub-0.2 μm mushroom gate both inside the wafer and from wafer to wafer.

The wide range of the A_3B_5 components for the different high frequency devices, integrated circuits and the systems on their basis has developed and manufactured in the republics of former USSR (mainly in Russia by authors of this paper and Ukraine - in research institute "Saturn", Kiev). They include:

- the low noise and high power GaAs MESFET's and P-HEMT's for the frequency range 1 - 65 GHz;
- IMPATT-diodes, Gunn-diodes, varactor-diodes, switching diodes for the frequency range 0.3 - 150 GHz, the mixer diodes for the frequency range 0.8 - 8 THz, the multiplying diodes for the frequency range 2 - 3 THz.

Using the above components the following receive-transmit moduls for the ultra high frequency (UHF) apparatuses were also developed and manufactured:

- the low noise amplifiers for frequency range 26 - 37 GHz ($G_{as} = 15 - 20$ dB and NF = 2.5 - 6 dB);
- the power amplifiers for frequency range 17 - 37 GHz ($G_{as} = 15 - 25$ dB, $P_{out} \cong 0.1 - 0.3$ W), $P_{out} \cong 2 - 4$ W at 8 - 12.5 GHz;
- switches, attenuators, phase shifters, limiters (0 - 18 GHz, 26 - 36 GHz);
- series of the GaAs-monolitic active 4-pole units for oscillators, covered the frequency range 3.5 - 17 GHz.
- the receive-transmit (R/T) moduls for the radio-relay communication lines in the frequency range 8 - 18 GHz.

The main areas of application of the GaAs-high frequency devices cover the radio-relay state and local communication lines, the Radar's, the satellite communications, the missile, the electronic warfare, the medical technique, the high frequency measurement technique, TV-technique and some other.

DIGITAL HIGH SPEED A_3B_5 IC

The A_3B_5-digital IC (DIC) technology has been developed since the late 1970's. It was based on the following n-type semiconductor structures:

- the ion implanted n-channel GaAs-wafers;
- the n-type uniformly doped GaAs epitaxial layers grown by MOCVD;
- the n-δ-(delta)-doped epitaxial layers grown by MOCVD and MBE;
- N-AlGaAs/GaAs HEMT-heterostructures grown by MBE;
- N-AlGaAs/InGaAs/GaAs strained pseudomorphic HEMT-heterostructures grown by MBE.

The different types of the FET-logic were used to design and fabricate DIC depending on the scale of integration and the speed of operation. They include: the buffer logic, the source coupled logic and the direct coupled field logic (DCFL).

The buffer logic and the source coupled logic, based on the depletion type of MESFET, were used to develop the very high speed IC of the small scale and the mid scale of integration (SSI and MSI). These IC were fabricated on the basis of the ion-implanted n-GaAs wafers and on the uniformly doped n-GaAs epitaxial layers grown by MOCVD. The direct coupled field logic (DCFL) based on the enhancement type and the depletion type of FET's was used to develop the large scale IC (LSIC). The LSIC's were fabricated on the δ-doped n-GaAs layers grown by MOCVD and on the N-AlGaAs/GaAs-heterostructures grown by MBE.

The special series of GaAs MSIC, operated at the clock frequency of ~1 GHz for the high frequency measurement technique was developed and manufactured in 1988 [3]. This series includes the different types of the logic gates, the clock flip-flop, the clock-wise counters, the 4-bit and 8-bit shift registers, the current switches, the double comparators, the selector-commutator 8→1, the 8-bit multiplexors and demultiplexors, the 16-bit multiplexors, the 4 GHz frequency devider, the 256 bit- SRAM and some other. On the basis of this high speed IC the following apparatuses for testing the high speed IC were manufactured:

- the generator of the code combinations "Gekkon" (V. Zabarauskas, Research Institute "Elita", Vilnus, Republica Livonia): f ≤ 1 GHz, for 4-bit combinations, the duration of the code combination is equal to 256 words;
- the pulse generator for f ≤ 2 GHz (V. Zabarauskas, Research Institute "Elita", Vilnus, Republica Livonia);

- the special system for testing the dynamical parameters of the digital GaAs IC (V. Zabarauskas, Research Institute "Elita", Vilnus, Republica Livonia);
- the system for testing the dynamic parameters of DIC: $f_{max} = 1$ GHz, duration of the time intervals ≤ 10 ps (A.A. Ostapenko, Research Institute of Precise Mechanics, Zelenograd, Moscow, and A. Balevsky, Central Institute of Computer Technique, Sophia, Bulgaria).

On the basis of the n-δ-doped GaAs-layers, grown by MOCVD, the special series of the digital GaAs-MSIC was developed in 1993 (IRE RAS, Moscow). The series contains: the pulse phase detector, the phase frequency detector, the different types of the frequency dividers, including the programmable frequency divider, the 3-bit-analog-to-digital converter, the selector-multiplexor, the high speed channel switcher, the three types of the logical levels translators: sin→GaAs (levels), sin→TTL (levels) and GaAs (levels)→TTL (levels). These IC's were used to develop the new generation of the high performance miniature navigation system.

The GaAs-δ-doping technique was used (first in USSR) to develop the GaAs LSIC's and VLSIC's [4,5]. Delta (δ-)-doping technique provides the highest uniformity and the highest values of the electron density and the rather good electron mobility in the device channel without the degradation of the barrier properties of the gate of MESFET. We note here only four of the developed GaAs LSIC's and VLSIC's: the 3000-gate array, the 16x16-parallel multiplier, the 16 K SRAM and LSIC of the 32 bit RISC-microprocessor. All of them were designed by using the DCFL-logic with the gate length $L_g \cong 1.2$ μm for E-MESFET. The typical value of the transconductance g_m of E-MESFET was 180 ÷ 220 mS/mm. The organization of the 3000-gate array corresponded to the "sea of gates" one. Each gate realizes the OR-NO-logic function. The delay time τ_d per gate and the power per gate measured by means of the ring oscillator were equal to 100 ps and 0.5 mW, respectively. On the basis of the 3000 gate array, the LSIC of the 16x16 parallel multiplier with the chip size of 5x5 mm^2 was developed with the input and output "0" and "1" - logic levels equal, respectively, to $U_L^0 = + 0.1$ V and $U_L^1 = +0.8$ V. The measured multiplication time τ_m was 10 ns and the power consumption P was 1.5 W.

The 16 K SRAM (4x4096 bits), developed in 1986, corresponded to the largest GaAs IC in USSR (~ 10^5 transistors) at that time. The size of chip was equal to 7.1x6.6 mm^2. The 16 K SRAM consists of the two blocks, each of 8 K. The typical value of the access address time τ_{AA} was 6 ns, and the power consumption was equal to 1.5 W.

In 1995 in IRE RAS the first Russian 32-bit GaAs RISC-microprocessor was developed on the basis of the δ-layer epitaxial structures. This GaAs LSIC contains 30000 transistors (with $L_g \cong 1$ μm) and has the clock frequency of 250 MHz which corresponds to $2.5 \cdot 10^8$ operations/sec. The operation of the microprocessor is based on the conveyer principle to address to the memory block and to other external blocks and moduls. The power consumption of the GaAs RISC-microprocessor was equal to 2 W.

The N-AlGaAs/GaAs - HEMT -technology was also investigated for developing the very high speed 1 K SRAM designed by using the DCFL-logic [6]. It was demonstrated (1986) that the use of HEMT-heterostructure opens the possibility to realize the VLSIC-SRAM with $\tau_{AA} \leq 1$ ns.

RESONANT TUNNELING NANOELECTRONIC DEVICES ON THE BASE OF THE ALGAAS/GAAS/ALGAAS QUANTUM WELLS

By using the effects of the size quantization and the resonant tunneling in the double barrier AlGaAs/GaAs/AlGaAs-quantum wells (QW's), the new type of ultra high speed devices - nanoelectronic devices was investigated (1993) in IRE RAS [7]. In the case of these devices the typical clock frequency as high as 20 GHz was realized even at the rather large electrode areas (~ 5x5 μm^2). The nanoelectronic IC of the 4 bit analog-digital converter and the EXLUSIVE OR (NOR)-logic gate were developed by using the QW-technology. It was shown, that in this case the same logic function with the much higher speed of operation and with the smaller number of the discrete components can be realized than in the case of the traditional microelectronics technology.

PROSPECTS FOR THE FUTURE

The analysis of the current situation in the field of the A_3B_5 device application and of the A_3B_5-device market shows that the most promising directions for the A_3B_5-electronics are the high frequency and ultra high frequency devices and MMIC's (f > 5-10 GHz), and some types of the very high speed digital and analog-digital IC's of the mid scale of integration (with clock frequency till 5-20 GHz), such as the frequency dividers, the analog-digital converters and some other.

Along with some new technologies, which can arise during the very fast development of the science and technology, the following directions can be considered as very promising for the future:

- HEMT-technology, based on the heterostructures with the higher electron density and electron mobility and with the satisfactory Schottky gate parameters for the UHF (till 200 GHz and higher) low noise and power devices. Along with P-HEMT N-AlGaAs/InGaAs/GaAs-QW-structures, the possible prospective candidate for this purpose is the N-InAlAs/InGaAs/InAlAs metamorphic heterostructures on the mismatched GaAs substrate with the controlable values of In-content and ΔE_C, μ_{2D} and n_{2D}, respectively;
- heterojunction bipolar transistors for the UHF power devices;
- resonant tunneling QW-structures for the UHF devices (till ~ 1 THz and higher), and for the high speed logic devices and IC's (with clock frequency $\geq$ 20-30 GHz).

CONCLUSION

The brief analysis of the present state of technology of the high frequency devices and the high speed integrated circuits based on the A3B5-semiconductor compounds in the republics of the former USSR, was presented. It was shown, that most promising directions for the future are:

- P-HEMT and metamorphic-HEMT technology for the high frequency devices and MMIC's (low noise and power devices). This technology can also be used for the digital SSIC's and MSIC's with the operating clock frequency higher than 10 GHz.
- Heterojunction Bipolar Transistor technology for the power devices and IC's.
- Nanoelectronic QW-technology for ultra high frequency devices and very high speed logic IC's.

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