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“High frequency and high speed microelectronics based on the A_3B_5-semiconductor compounds in the republics of the former USSR. Present state and prospects for future”

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ABSRACT

Present paper is devoted to the 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.

1. 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 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 value of 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 (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 combination of the optical and electronic devices at the same chip is realized. 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 Shottky diodes, p-i-n-diodes, Gunn-diodes, the resonant tunneling quantum well-structures were widely used.

2. A_3B_5 High Frequency Analog Devices (HFAD)

During 20 years A_3B_5 - HFAD technology has passed the way from the GaAs-MESFET-technology, based on the n-doped epitaxial layers, grown by LPE and MOCVD untill the High Electron Mobility Transistors (HEMT’s) based on the lattice-matched N-AlGaAs/GaAs heterostructures, pseudomorphic N-AlGaAs/InGaAs/GaAs heterostructure quantum wells and metamorphic N-InAlAs/InGaAs/InAlAs heterostruc-tures on the mismatched GaAs, 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 in the device channel and the reduction of the gate-channel distance and the thickness of the electron channel. 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 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.

in IRE RAS, is based on the combination of the precesion 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 range of the A_3B_5 components for the different high frequency devices, integrated circuits and the systems on their basis has developed and it is manufactured at present time in the republics of former USSR (mainly in Russia and Ukraine).

They include:

- the low noise and high power GaAs MESFET's and P-HEMT's for the frequency range 1 - 65 GHz;
- IMATT-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) apparatus were also developed and were manufactured in Russia and Ukraine:

- 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-monolotic active 4-pole unit 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. Each R/T-module includes the input receives and the output transmitter.

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

3. Digital High Speed A_3B_5 IC

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

- the ion implanted n-channel GaAs-wafer;
- the n-type uniformly doped GaAs epitaxial layers grown by MOCVD;
- the n-δ-doped epitaxial layers grown by MOCVD and MBE;
- N-AlGaAs/GaAs HEMT-heterostruc-tures grown by MBE;
- N-AlGaAs/InGaAs/GaAs strained pseudomorphic HEMT-heterostruc-tures grown by MBE.

The different types of the FET-logic were used to 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 (DSFL).

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 and 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 devepletion 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 manufactored (1988). 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 switch, 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 SRAM and some other. On the basis of this high speed IC the following apparatus for testing the high speed IC were manufactured:

- the generator of the code combinations "Gekkon" (Republica Livonia, Vilnus): $f \leq 1$ GHz, for 4-bit combinations, the duration of the code combination is equal to 256 words;
- the pulse generator (Republica Livonia, Vilnus): $f \leq 2$ GHz;
- the special system for testing the dynamical parameters of the digital GaAs IC (Rep. Livonia, Vilnus);
- the system for testing the dynamic parameters of DIC: $F_{max} = 1$ GHz, duration of the time intervals ≤ 10 ps (Moscow and Sophia).

On the basis of the n-δ-doped GaAs-layer, grown by MOCVD, the special series of the digital GaAs-MIC was developed in 1993. 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 (level), sin→TTL (level) and GaAs (level)→TTL (level). These IC's were used to develop the new generation of the high performance miniature navigation system.

The δ-doping GaAs-technique was used (first in USSR) to develop the GaAs LSIC and VLSIC. Delta (δ-)-doping technique provides the highest uniformity and the highest values of the electron density and the 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 and VLSIC: 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 of $\cong 1.2$ 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 was corresponded to the "sea of gates". 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 equaled 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 equaled, respectively, to $U_L^0 = +0.1$ V and $U_L^1 = +0.8$ V. The measured multipli-cation time τm 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 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 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 and has the clock frequency of 250 MHz which corresponds to $2.5 \cdot 10^8$ operations/sec. The principle of the operation of microprocessor is based on the conveyorization of the access to the memory block and 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. It was demonstrated (1986) that the use of HEMT-heterostructure opens the possibility to realize the 1 K-SRAM with $\tau_{AA} \leq 1$ ns.

4. Resonant tunneling nanoelectro-nics devices on the base of the AlGaAs/GaAs/AlGaAs quantum wells

By using the effects of the size quantization and the resonant tunneling (RT) 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 the case of these devices the typical clock frequency as high as 20 GHz was realized even at the rather large electrode area (~ 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.

5. Prospects for the future

The analysis of the current situation in the field of the device application and of the A_3B_5-device market shows that the most promising directions for the A3B5-electronics are the high frequency and ultra high frequency devices and MMIC (f ≥ 5-10 GHz), and some types of the very high speed digital and analog-digital IC of the mid scale of integration (clock frequency till 5-20 GHz), such as the frequency deviders, the analog-digital converters and some other.

Along with some new technologies, which can arise during the very fast science and technology development, the following directions (according to our opinion) 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 satisfactory Shottky gate parameters for the UHF (till 200 GHz) low noise and power devices (the possible candidate is the N-InAlAs/InGaAs/InAlAs metamorphic heterostructures);
- heterojunction bipolar transistors for the UHF power devices;
- resonant tunneling transistors for the UHF devices (till ~ 1 THz and higher), and for the high speed switching devices and IC (with clock frequency ≥ 20-30 GHz).