SEMICONDUCTOR DEVICES IN MILLIMETRE WAVE RADIO SYSTEMS

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1. Introduction.

The millimetre wave (MMW) frequency region is of more and more interest for wide band telecommunication and imaging systems, material spectroscopy, medical treatments, collision avoidance radars and other applications. In spite of the problems in technology, higher price of basic components in comparison with those at microwaves MMWs meet expanding interest of the consumers, and are considered as the most challenging communication service of the current decade. High level of absorption in the atmosphere, that limits the application of MMW in telecommunication systems, can be used for to improve the confidentiality of wireless telecommunication systems and provide multipoint interactive video service, indoor communications and wireless access to local area networks. MMW imaging is not so influenced with smoke, fog, and atmospheric drops. Therefore it has significant advantages over optical and infrared one. Discovering of the objects, covered with dielectric materials, is possible at MMW and specific lines in the absorption spectrum give new tools for indication of insertions (e.g. water in the oil) and atmospheric pollutions. Positive influence of MMW irradiation to human body is now used in medical treatments. Doppler radars give appropriate accuracy and space resolution to provide collision avoidance in any weather. In some cases the functions of collision avoidance and telecommunication systems can be combined.

2. Fundamental limitations of the cut-off frequency.

Most of the needs in power sources for the systems, mentioned above, could be delivered with low power level equipment (< 50 mW), so semiconductor devices are appropriate. Besides, the later are compatible with low-dimension microstrip antennas that give opportunities for portable performance of the setup. The sensitivity of modern low-noise transistor amplifiers is comparable with superconductor devices at low temperatures and at the room temperatures they have no competitors. Meanwhile there is a common trend for all semiconductor devices: deterioration of their parameters with frequency growth. At frequencies over 100 GHz these deteriorations look awful. There are many sources of this problem and some of them can be eliminated by improvements in device technology and design. Another part, that is resulted with fundamental properties of the materials and principals of the device operation as a rule cannot be simply removed and must be the subject of special consideration to find the approach in technology and design, feasible to millimeter wave operation. This problem is, in particular, discussed in [1].

Most important limitation of the cut-off frequency for transistors, Gunn diodes and IMPATT diodes, which are now the main solid state devices in MMW radio systems, is due to the fact, that their operation is based on the drift and (or) diffusion of free charge carriers – electrons or holes. So, there is always a specific transit time, which depends on the drift velocity and thickness of the active zone of the device and this predicts a cut-off frequency near the value $f_\tau = t/v$, where t is corresponding thickness, v – velocity. The drift velocity is limited in the semiconductors at the level $\div 10^7 cm/s$ due to the electron scattering and thickness is limited by physical (e.g. high-field domain size in Gunn diode) or technological reasons. Electrical break-down, problem of the heat-sink, special demands to the device impedance for good matching with feeders result in the drop of the output power at frequencies over 100 GHz to the level <1mW, that is too small for the telecommunications and other important applications.

Schottky barrier diodes are still the most employed nonlinear elements of MMW detectors, mixers and frequency multipliers. Frequency limitations in this case are mostly due to parasitic series resistance R_S according to the definition of cut-off frequency $f_c = 1/2\pi R_S C_B$, where C_B is barrier capacity. Normally, when epitaxial n-layer on the high-doped semiconductor substrate is used for diode performance, reducing of contact size for to reduce C_B results in increasing of R_S due to current spread effect. So, further enhancement of Schottky diode parameters is possible, if the epitaxial growth of n-GaAs and Si on the metal-like substrates will be developed, that can give a considerable reducing of R_S.

3. Waveguide and quasi-optical performance of MMW semiconductor devices and integrated circuits.

Two-terminal devices are compatible with metal single-mode waveguides. In the case of low device impedance special matching "caps" are used, and for small-size contact whisker bonding or contacting is performed. Metal waveguides provide a good heat-sink that is very important for MMW devices. Despite a relatively small size of the rectangular waveguides, that give many technical problems in their manufacturing, this type of device performance is widely employed in some cases even at frequencies as high as 500 GHz. Three-terminal devices are more compatible with microstrip lines and as a rule are integrated with other elements in hybrid or monolithic integrated circuits. In the later case semi-insulating GaAs or InP are used as dielectric for microstrip waveguides. The problems of heat-sink, when increased power is necessary, are solved with on-chip mounted devices or power combiners. Nevertheless, as was shown above, the main trend, connected with increasing the operation frequency, is the deterioration of the most important parameters of semiconductor devices. Besides propagation losses at millimetre waves in single-mode metal

waveguides and microstrip lines are much higher than at microwaves and increase drastically with increasing frequency. Therefore the quasi-optical performance of MMW circuits is often preferable. Meanwhile the small size of microstrip antennas offers the opportunity to create a big family of antenna-coupled active and nonlinear semiconductor devices for multi-beam receivers, power combiners and imaging systems. Recent performance of Gunn-diode oscillator, combined with log-periodical microstrip antenna was demonstrated in [2].

The main problem in quasi-optical performance of semiconductor devices is to provide appropriate matching with the radiation feed. As the electromagnetic waves in quasi-optical systems are propagating in a form of the beam with certain amplitude variation through the cross-section, some kind of antenna is necessary to concentrate the radiation energy in the small-size semiconductor device. Recent achievements in the technology of beam-lead diodes have led to their dominating role in quasi-optical constructions for millimetre wave and submillimetre wave circuits. The common feature for all quasi-optical systems is that their transverse dimensions are large compared to the wavelength. The longitudinal size of the resonator system is also large compared to the wavelength to eliminate as far as possible undesirable modes and normally it is large compared to the transverse size. So there is a wide area of opportunities to mount many semiconductor devices integrated with a resonator structure. It results in various constructions of power combiners and focal plane receivers, formed as multi-element arrays. In particular, the problem of heat-sink is solved in quasi-optical structures due to the separation of heat-generating devices in space.

The advantages of open resonator oscillators at millimetre wave frequencies are mainly due to high quality factor and practically convenient sizes, that can be used, particularly, in narrow band Gunn oscillators with improved stability. In some cases metallic gratings or hybrid dielectric slab waveguides are combined with the quasi-optical resonator system. A grating provides necessary impedance matching of devices with the resonator and also acts as a heat sink.

4. Self-forming effects in small-size contact formation.

The problem of small-size contacts arises in the technology of millimetre wave devices due to requirements to decrease barrier capacitance of Schottky diodes and to damp the heating effects in the Gunn diodes and similar devices. Practical solution of the problem for Schottky diodes was found in the performance of honey-comb structures, using high resolution photo- and electron-beam lithography. In the case of Gunn diodes ohmic contact performance employs a thermal annealing of Au+Ge thin film at the n-GaAs surface. Honey-comb performance is also possible due to the collection of Au atoms into the as prepared windows in SiO_2 cover. Thermomechanical strains due to the difference in thermal coefficients for Au, GaAs and SiO_2 play a very important role in this process, actually demonstrating a self-forming effects.
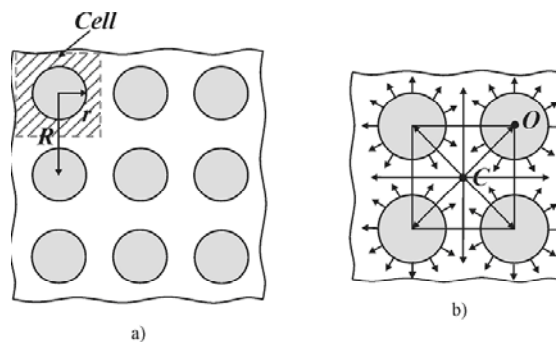

Fig.1. Typical view of "honey-comb" structures. a) top view; b) schematic of thermo-mechanical strains.

5. Active dielectric waveguides.

Since the invention of the tunnel diode – the p-n structure with degenerated electron gas, that offered the negative slope of current-voltage characteristics ($dI/dV < 0$) (Esaki, 1958) the problem of active waveguides was studied and discussed many times. In particular, it was applied to the semiconductor devices based on the bulk negative resistance (BNR) performed as a microstrip waveguide. If the size in the direction of wave propagation is comparable with the wavelength, it can be considered not as a discrete device but as active waveguide. In the millimeter wave range the wavelength in the microstrip waveguide, filled with semiconductor, is small enough, so distributed amplification of the traveling electromagnetic wave turns to be practically possible.

The most promising BNR is that arises in A^3B^5 semiconductors due to intervalley scattering of the electrons in high electric field. The advantage of this mechanism is that all the semiconductor media that fills the waveguide structure is or may be active. The problem is, however, that the semiconductor contains free charges (electrons), so the process of electromagnetic wave propagation is strictly connected with space charge wave traveling. The electromagnetic theory of such a waveguide is considerably different in comparison with theory of waveguides (microstrip lines) on the ideal dielectric, in which the ohmic current may be neglected. It was developed, particularly in [3].

The first experiments on electromagnetic wave amplification due to negative resistance in stabilized GaAs structures were performed with the coplanar microstrip waveguides. The electric field was applied to the metal thin-film strips, which were at the same time the ohmic contacts to *n*-GaAs epitaxial layer on the semi-insulating GaAs substrate. The advantage of planar geometry is that stabilization of high field distribution is due to the dielectric substrate that suppresses the high-field domain excitation. The thickness of the active *n*-layer must be small to satisfy the stability criteria $nt \leq 2 \cdot 10^{11} \text{cm}^{-2}$. The distance between the metallic strips is not limited by this condition and may be as long as 100 μm and more. This imposes an appropriate and sufficient heat-sink when high bias electric field is applied. Nevertheless, the coplanar active waveguide amplifiers were not practically used because of high noise level and insertion losses.

The experiments with active fin-line on GaAs were performed at the frequency 40 GHz. The compensation of losses ~10 dB was demonstrated in the pulse regime. Further advance of this amplifier was not successful because of too heavy conditions of heat-sink and high insertion losses in the metallic strips.

The problem of heat-sink turned to be common for all the waveguide constructions: bulk negative resistance is realized in GaAs and other semiconductors at high electric field ($>10^3$ V/cm) and current density ($\geq 10^3$ A/cm^2). So the thermal heating is too intensive for the amplification in dc regime that is of practical interest. Besides, the noise level due to the electron heating is higher than in the field-effect transistors, despite that they operate approximately at the same conditions. Future prospects of such amplifiers are possible, if BNR is realized at lower current densities, e.g. $\leq 10^2$ A/cm^2. Some evidence of this opportunity with resonance-tunneling structures was theoretically shown, so the turn back to active waveguide on the semiconductor with bulk negative resistance is possible in the future.

6. Slow-wave amplification in DRW.

The idea of traveling wave amplification in the semiconductor with a drifting electron flow analogous to vacuum TWT is well known since the work of L. Solimar and E. Ash (1967). The experimental demonstrations were performed at microwave frequencies, though it was clear that only at millimeter waves this mechanism is of the practical interest due to short electromagnetic wavelength. The problem was to find a type of the delay structure, which could provide a sufficient decrease of the phase velocity ($\geq 10^3$) without considerable dispersion at MMW frequencies. Periodically corrugated image waveguide turned to be an appropriate structure. Following this idea in [4] *i-n-i*-GaAs epitaxial structure were used as image-type waveguides.
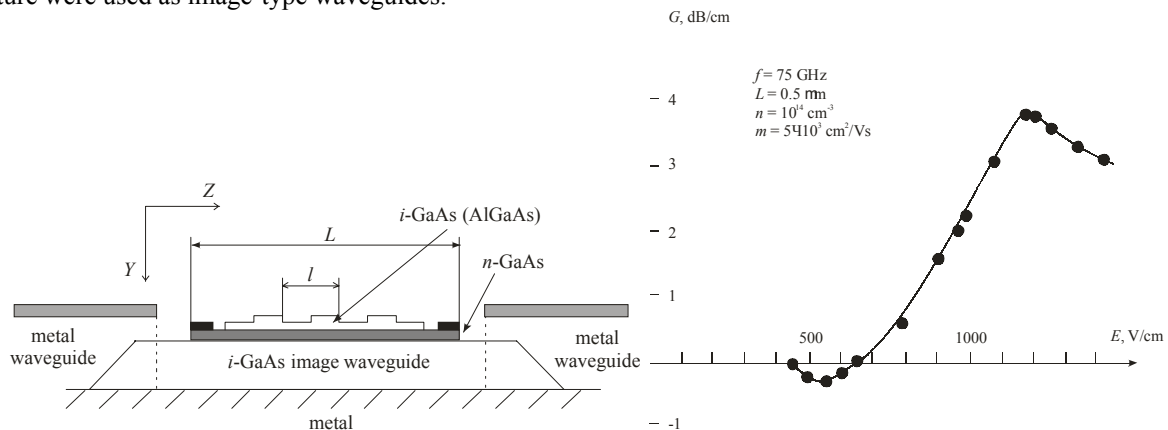

Fig.2. Traveling wave amplification in GaAs-based dielectric waveguide structure.

Thin epitaxial *n*- and *i*-layers were formed in the growth process by MOCVD. Electromagnetic wave deceleration was performed by using the corrugated periodic grids. Submicrometer corrugated delay structures were manufactured by holographic lithography combined with dry plasma or photochemical etching. The delay structures had a period of 0.5-1.0 μm with 0.1 μm groove depth. The *n*-type layer electron concentration was 10^{15}-10^{16} cm^{-3}.

The 'electronic' gain as a function of bias electric field was observed, qualitatively in accordance with theory. Note, that the value of threshold field (650 V/cm) is considerably lower than the electric field value in the most of millimeter wave semiconductor devices. Therefore the traveling wave-type amplification seems to be promising for the design of low noise millimeter wave devices and integrated circuits.

7. Multilayer dielectric waveguides.

As it was shown above, new opportunities for active devices appear if dielectric rod waveguide (DRW) contains thin-film semiconductor or other special materials (ferrite, or nonlinear dielectric). In [5] the DRW was made of the epitaxial structure, consisted of 0.1 μm thick, $n \sim 10^{16}$ cm^{-3} epitaxial layer at *i*-GaAs substrate. The shape of DRW was estimated for matching with metal waveguide both at the input and the output side. The electromagnetic wave propagation parameters in 75-110 GHz frequency range with 3 mW input power were measured with HP 8510 network analyzer.
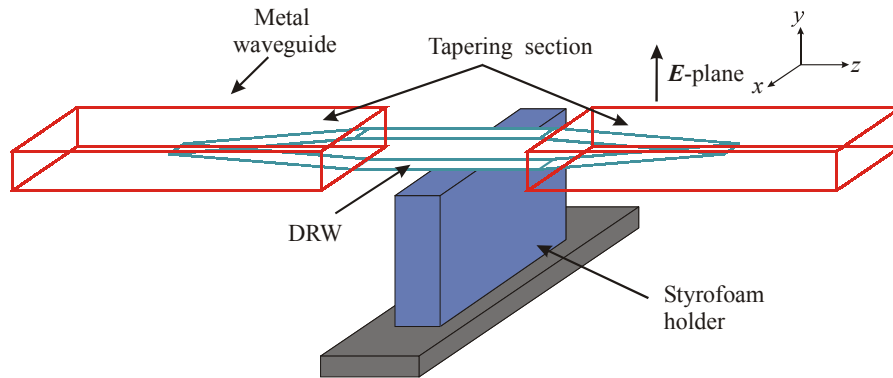
Fig.3 Experimental setup of wave propagation in DRW.

It was shown that the parameters of the wave propagation are in the noticeable dependence on the electric field direction in the case of n-layer presence at the GaAs surface. For i-GaAs DRW without n-layer and for the case when **E** parallel to n-layer the frequency dependences are quite smooth with some additional attenuation and phase delay. When the electric field is normal to n-layer, frequency dependences look like irregular and not correlated with results of computer simulation for two-layer model. The mode transformation effect was particularly seen in this case, when n-layer is normal to the electric field component of the propagating electromagnetic wave. The most adequate explanation of this as like as the frequency dependences of the losses and phase delay in such DRW is that electromagnetic wave is transformed due to the presence of potential barrier capacitance at the interface of the n-layer and i-GaAs substrate. It offers new opportunities for frequency multipliers and other devices, based on the varactor effects. The transformations in the surface and near-surface layers of GaAs under electromagnetic wave irradiation should be also taken in account.

8. Conclusions.
This analysis of semiconductor device applications in millimetre wave systems shows, that saturation of electron drift velocity in semiconductors due to the hot electron effects in high electric fields turns to be a serious fundamental limitation on the way of increasing the device operating frequencies above 100 GHz. This problem may be solved partially by the optimized choice of semiconductor materials, employing of heterostructures with two-dimensional electron gas and quantum effects, such as resonant tunneling. Ballistic transport and other high-speed phenomena in semiconductors are also of interest for the device performance.
The limitations of output power are affected by the limited heat conductivity of solids and low efficiency of semiconductor devices at MMW. Recent achievements in the technology of A^3N semiconductors can give new enhancements in this aspect.
Due to the relatively small wavelength a new approach, different from that at microwave frequencies and closer to optical systems, may be used at MMWs: integration to quasi-optical systems in a form of arrays of antenna-coupled devices and performance of the devices as active waveguides. Self-forming effects can be used for small-size metallization and near-surface transformations in semiconductors are important in the process of MMW device performance.

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