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Current Instabilities in Vacuum Electron Devices and Semiconductor Avalanche Diodes for Generation of THz Oscillations

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***Abstract*— Two promising methods for generation of THz radiation are presented and discussed. The hybrid bulk-surface modes excited in a cavity with bi-periodic grating have been considered. Such modes appear due to Electrodynamic interaction of the bulk modes with surface-wave resonator modes (i.e., leaky spoof surface plasmon polariton of an open grating). The potential for the effective generation of the THz radiation in a Clinotron by the excitation of the hybrid modes has been demonstrated. Theory of a new instability in reversed biased pn-junctions with impact ionization was developed and applied for investigation of THz oscillators design.**

Keywords—Clinotron, Diffraction Radiation Oscillator, Hybrid Resonant Mode, THz oscillations, current instability in avalanche diode.

I. Introduction

Nowadays a lots of research teams are working worldwide on dismissing so called 'Terahertz (THz) Lag' developing both vacuum and semiconductor electron devices capable of generating electromagnetic oscillations in sub-THz and THz frequency ranges. Current state-of-the-arts is shown schematically in Fig. 1 below.

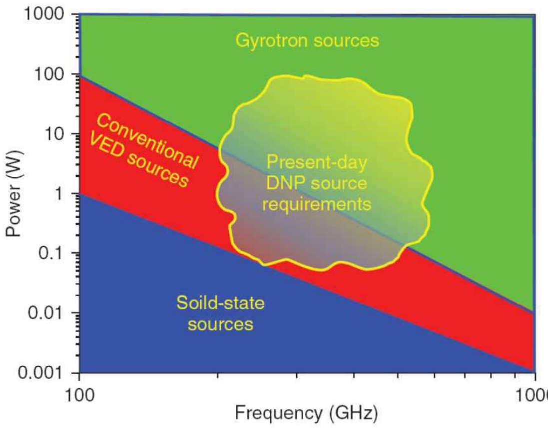

Fig. 1. Power vs Frequency diagram for THz Electron Devices

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In the O.Ya.Usikov Institute for Radiophysics and Electronics NAS of Ukraine (IRE NASU) such research has been carrying out since the 50-s years of the XX century. In particular, a series of Resonant Backward Wave Oscillator (BWO) has been developed in sub-THz frequency range. This vacuum tube uses extended interaction of electron beam with slow wave of periodic grating. Since electron beam in this BWO is *inclined* with respect to the grating surface, the device was named as *Clinotron* [1]. Such configuration enabled essential enhancement of the above interaction efficiency with increasing the working frequency which is crucial when designing THz oscillators [1]. Diffraction Radiation Oscillator (DRO) was also suggested and developed in the IRE NASU [2] (called outside Ukraine as *Orotron*), is a Vacuum Electron Device also generating sub-THz (*or millimeter wave*) oscillations [2,3]. In those devices, the bulky modes in open resonator with periodic grating are excited by EB due to Diffraction Radiation or Smith-Purcell effect [4,2]. For further progress in THz Clynotrons design we proposed and studied excitation of hybrid, *bulk-surface*, modes in a cavity with bi-periodic grating [5,6].

For design of efficient THz *semiconductor electron device,* we suggested application of the revealed earlier by us a new current instability in the reverse-biased asymmetrical **pn**-junctions in impact ionization regime [7]. In the Sections II some IRE NASU achievements in design of THz Vacuum Electron Devices are presented. Section III presents theoretical results on a new current instability in reverse biased **pn**-junction with impact ionization which is more suitable for generation of THz oscillations in comparison with conventional IMPATT diodes.

II. THz Vacuum Electron Devices

Packed 'THz Clinotrons' suggested and developed in the Usikov IRE NASU [1], operate in sub-THz range with maximal frequency up to 0.41 THz [2-3]. Fig.2 shows schematic cross-section of sub-THz Clinotron (a), it's appearance (b), and field patterns in BWO mode (c) and Hybrid mode (d).

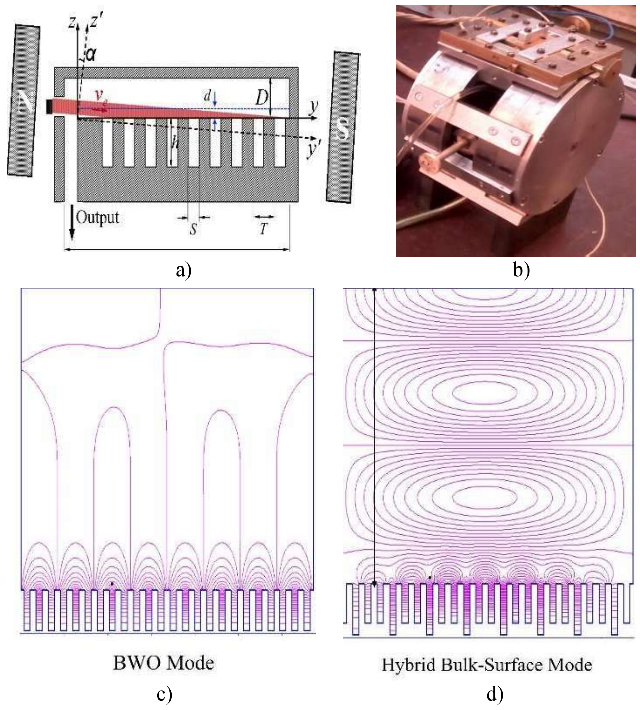

Fig.2. Schematic cross-section of THz Clinotron (a); packed Clinotron appearance (b); field patterns in BWO mode (c) and Hybrid mode (d).

Recently, we discovered and studied a new, Hybrid (*Bulk-Surface*), mode instability in the Clinotron with resonant system, containing bi-periodic grating enabled efficient excitation of THz oscillations [8] and a wide range of frequency tuning. The field patterns in Hybrid mode are shown in Fig.2, d. In the Table 1 one may see the main performance for different types of the developed sub-THz Clinotrons operating in the frequency range from 0.035 up to 0.4 THz. The 'THz Clinotrons' typically operate within the beam voltage range from 2.5 kV up to 5.5 kV, and the electron beam (EB) current does not exceed 200 mA. Sheet electron beam of 'THz Clinotron' tubes might be focused by permanent magnet focusing system with static magnet field induction ~1 T.

TABLE I. BASIC PERFORMANCE OF *CLINOTRONS*

***Clinotrons* developed in IRE NAS of Ukraine**					
Type	Frequency, THz		Output Power, *W*		Magnetic Field, *T*
	min	max	Typical	Max	
Clinotron-8	0.035	0.038	10	25	0.35
Clinotron-4	0.070	0.078	4	10	0.35
Clinotron-3	0.088	0.100	2	5	0.35
Clinotron-2	0.125	0.140	1	2	0.35
Clinotron-175	0.165	0.177	0.5	1.2	1
Clinotron-260	0.240	0.265	0.1	0.3	1
Clinotron-300	0.275	0.305	0.07	0.15	1
Clinotron-340	0.320	0.355	0.05	0.1	1
Clinotron-400	0.340	0.405	0.02	0.05	1

The water cooling of Clinotron is required for its temperature control. For instance, the packed '0.4 THz Clinotron' sample designed for generation of 0.4 THz continuous wave (CW) oscillations actually may generate oscillations within 0.34 THz – 0.41 THz frequency range when varying the accelerating EB voltage within the range from 2.6 kV up to 4.3 kV [2]. For these voltage values, the '0.4 THz Clinotron' has it's starting current ~ 61 mA. It was also tested in EB current range from 65 mA up to 200 mA which showed its averaged power ~20 mW and frequency tuning range ~ 20%. In the narrower frequency range (0.37 – 0.387) THz, the maximum output CW power was ~ 43 mW.

Such modification of Clinotron as Weak Resonant BWO (WR-BWO) has been suggested for generation of wideband chaotic/stochastic sub-THz oscillations [9-12]. Clinotrons and their modifications are in wide use for many applications. Only some of them are listed below. WR-BWO (based on Clinotron) was used in design of chaotic/stochastic signals generator for the first Noise Radar [13] and Noise Radar Technology [14. The Clinotron for generation of 0.3 THz oscillations was developed [3] for the pumping module in high-field dynamic nuclear polarized (DNP) targets for applications in nuclear magnetic resonance (NMR) spectroscopy. It provides CW output power up to 100 mW in the frequency range from 0.29 THz to 0.31 THz.

Another Clinotron was designed for the thermographic alignment of the quasi-optical transmission lines in the CTS-diagnostic at the W7-X Stellarator (Germany) provides CW radiation power ~ 1 W in the frequencies range from 0.172 THz up to 0.175 THz [15,16].

III. CURRENT INSTABILITY IN REVERS BIASED ASYMMETRICAL PN-JUNCTION

For numerous real applications there is also need in a compact and low voltage THz source, even with lower levels of output power compared to that of vacuum electron devices. However, the well-known semiconductor devices, such as IMPATT-, Gunn-, Tunnel-diodes and transistors have constrains not allowing their usage in THz frequency range. That is why, the common way of having THz sources is based on frequency multiplication of microwave signals.

We have been studying spatial and temporal dynamics of current densities and electric fields in reverse biased multilayered semiconductor structures within the frame of drift-diffusion model (DDM) of semiconductors. The related system of differential equations consists of continuity equations for electron and hole current densities and Poison's equation for electric field, accounting both generation of the charge carriers due to impact ionization and their recombination. Unlike earlier approaches we take into account mutual dependence of depleted layers width on the charge of the generated electron-hole pairs and current densities and electric fields. When studying reverse biased multilayered semiconductor structures we revealed new current instabilities, both regular and chaotic ones [7,17-20]. The most promising for design of an efficient source of THz oscillations is a new *current instability* in reverse biased asymmetrical **pn**-junction with impact ionization [16-18]. This instability takes place only in **pn**-junction with geometrical and doping asymmetries of its **p-** and **n-**layers [16-18]. In the basis of this current instability lays the physical mechanism consisting in compensation of the built-in electric potential by the charges generated in the impact ionization layer, which is inside the depletion layer of the inverse biased **pn**-junction. To reach an essential compensation of the built-in potential, that may lead to decrease of the total field in the impact ionization layer, one has to provide a sufficiently high doping rate of impurities in the **pn-**junction. In turn, decrease of the static electric field causes the lowing the impact ionization coefficient, which decrease the number of generated charges and, hence, the compensation rate of the built-in potential, and so on. For justification of such instabilities, we did numerous simulations within the drift-diffusion model of classical semiconductor devices. As an example, Fig.3a shows electron-current and hole-current densities across a **pn-**junction at different time instances of self-oscillations which are numbered from 1 through 11. Distributions of the E-field across the pn-junction at different time instances are show in Fig.3b and numbered according to Fig.3a. One may readily trace the mutual dependence of the generated current densities and the E-field: when the currents decrease (increase) the E-fields increase (decrease) in that type of current instability. The maximal frequency of such oscillations is defined by minimal time needed for the generated carriers to fly out of impact ionization layer. As the latter is much narrower of the depletion layer the maximal frequencies in the diode based on that current instability may be much higher compared to the case of conventional IMPATT-diode. In addition, to obtain a negative differential conductivity there is no need in an external cavity, like in the case of IMPATT-diode. An external oscillatory system is needed just for the electromagnetic fields excitation with the oscillating current. Open Resonator might be one of an appropriate oscillatory system.

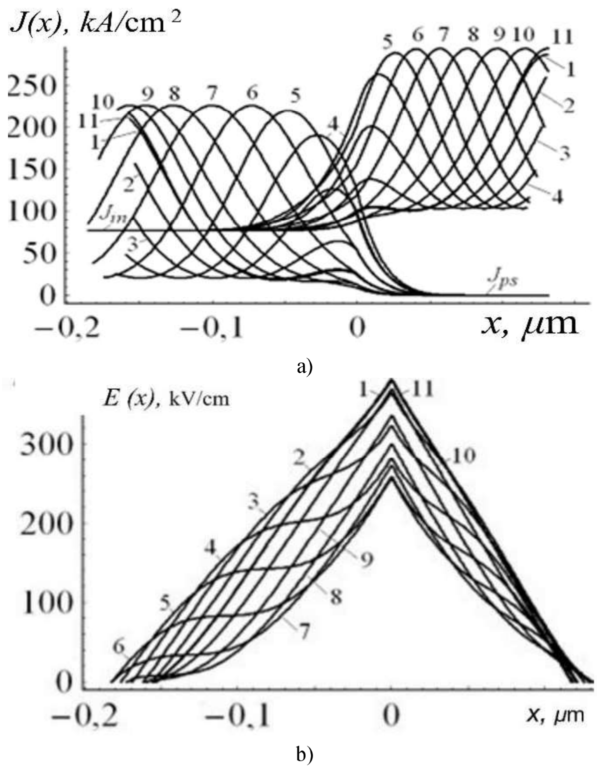

Fig.3. Current self-oscillations in reverse biased **pn-**junction with impact ionization: (a) electron- and hole-current densities across **pn-**junction at different time instances numbered from 1 through 11; (b) distributions of E-field across the **pn-**junction at the same time instances similarly numbered.

For abrupt **pn-**junctions, we developed we developed a new efficient numerical method enabled simulation of spatial-temporal dynamics of currents and field in such **pn-**junctions.

We have studied variety of oscillatory regimes due to revealed current instability: self-oscillatory and forced oscillatory regimes; generation with DC current injection; single and double frequencies generation; multi-frequency and chaotic self-oscillatory regimes. The major simulation was done for different semiconductor materials: Silicon (Si), Germanium (Ge), Gallium Arsenide (GaAs) and Indium Antimonide (InSb). Typical doping rates of impurities were about (10^{16} - 5 10^{17}) cm^{-3} and never exceeded 10^{18} cm^{-3} value.

For reducing the currents densities ensuring a partial compensation of the electric field created by the charge of impurity atoms we analyzed the current self-oscillation modes in an asymmetrical **pn-**junction. Multiple simulations of self-oscillatory regimes in Si, Ge and GaAs **pn-**junctions was performed for a wide range of the impurity atoms concentrations, injection current densities, and reverse bias voltage. The frequency of the current self-oscillations in Si, Ge and GaAs ***pn***-junctions falls into the microwave and THz range and can be properly approximated by the following formula: $f = (v_{ns} + v_{ps})/2\bar{w}\delta_s$, where δ_s is matching coefficient which equals 0.515, 0.65, and 0,635 for GaAs, Si, and Ge, respectively. Fig. 4a shows highly anharmonic, relaxation, self-oscillations of the avalanche hole-current density *J*(t), (kA/cm^2) in the depletion p^+–region of GaAs $\mathbf{p^+n}$-junction for $U/U_{av} = 2.05$; $N_a = 2\ 10^{17} cm^{-3}$; $N_d = 2\ 10^{16} cm^{-3}$. Fig.4b, displays the Fourier spectrum *J(f)* of relaxation self-oscillations of the avalanche hole-current density presented in Fig. 4a. Spectral lines *1*, *2*, and *3* represent the first, second and third harmonics of the relaxation self-oscillations: $f_1 = 0.494\ THz$, $f_2 =$ 0.988THz; $f_3 =$ 1.482THz.

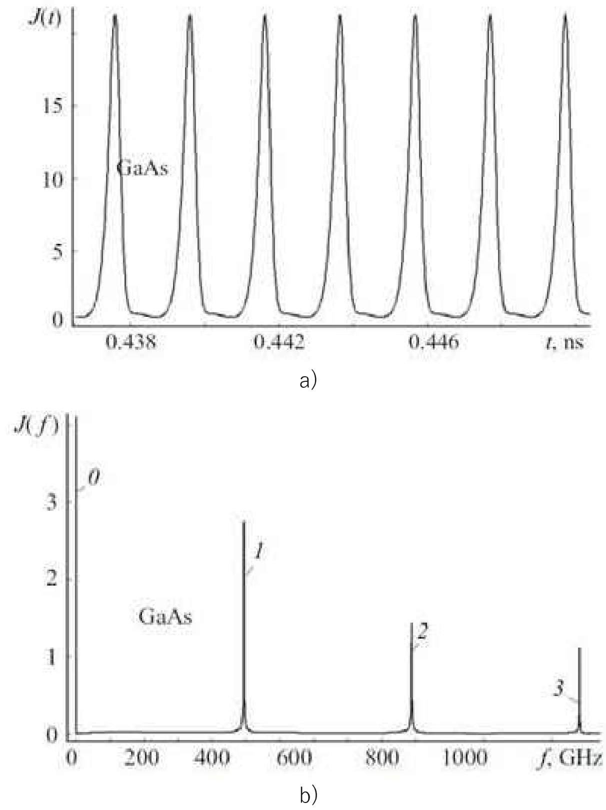

Fig.4. Reverse biased asymmetrical GaAs $\mathbf{p^+n}$-junction: (a) steady-state relaxation oscillations; (b) Fourier spectrum of relaxation oscillations.

It has been shown that for typical dimensions of **p-** and **n-** areas and reverse biased voltages < 100 V the suggested device may generate oscillations from 0.01 THz up to 0.5 THz for the first Fourier harmonic. When highly anharmonic regime is achieved (Fig.4a), the second and third harmonics have appreciable output power with frequencies 1 THz and 1.5 THz respectively (Fig.4b). In chaotic oscillatory regimes, the wideband and ultrawideband random THz signals are generated with power spectral density width ~ 2 GHz and ~20 GHz, respectively.

We also considered a possibility to generate THz oscillations in a circuit containing highspeed low power semiconductor diodes coupled via strip-lines forming distributed resonator. In particular, in the regimes when time-delay in feedback became essential to create a complicated self-oscillatory mode enabling generation of extremely high frequency up to 1 THz [21]. The models that consist of discrete lumped circuits of active and passive devices and distributed sections of microstrip lines connecting the lumped circuits have been studied for different frequency bands [21]. Gunn diodes and the resonant tunneling diodes (RTD) operating in the EHF frequency band have been considered as active devices in those models. Parallel and series connections of microstrip sections with active devices have been simulated. Other structures like a 2D microwave cavity with a wall covered with active devices and a 1D open resonator. Simplified models for simulations of field dynamics were developed, which rely on the method that reduces the initial-boundary problems for the wave equations in structures with lamped active devices to the initial problems for time-delay nonlinear equations of difference and difference-differential type [22, 23]. When using appropriate values of circuit parameters and choosing the RTD operating at sufficiently high frequencies, one can make the circuit to generate a train of short sub-THz pulses, which are emitted into an open microstrip section or antenna. At the same time, if the chosen Laser Diode is also a highspeed device, a similar train of optical pulses would be radiated, which are synchronous with original sub-THz pulses [21].

IV. Conclusion

The sub-THz vacuum electron devices developed in IRE NAS of Ukraine (Clinotrons and DROs) are CW high power devices, which are used in many various applications. The suggested concept for design of a new subTHz and THz semiconductor oscillators is very promising for development of a compact low voltage THz devices. We believe that with access to advanced semiconductor technologies will enable development of promising THz oscillators. All suggested devices and regimes may be used for design of advanced systems in photonics, laser, nanooptics and nano-sensors.

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