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SUB-THZ AND THZ CURRENT INSTABILITIES IN SEMICONDUCTOR SELF-OSCILLATORY AVALANCHE DIODES

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Abstract. *Nowadays, the most common way of getting a THz source is based on frequency multiplication of microwave signals or on the two lasers frequencies mixing to produce a THz signal as the difference of the two optical frequencies. Development of a self-oscillator in THz frequency range is a challenging task for nowadays technology. The discovered current instability in reverse biased* ***p-n*** *junction may be used as the basis for design of a new type of sub-THz and THz semiconductor self-oscillators, named as Self-Oscillatory Avalanche Diodes (SOAD) - compact, low-voltage THz sources. The SOADs may be used for design of advanced THz sources for radar, communications and imaging systems.*

Keywords*: THz and sub-THz oscillations, current instability in self-oscillatory avalanche diode, chaotic instability, radar,*

1. Introduction

Nowadays, the most common way of getting a THz source is based on frequency multiplication of microwave signals or on the two lasers frequencies mixing to get a THz signal as the difference of the two optical frequencies. However, for numerous realistic applications there is need in a compact and low voltage THz source. The well-known semiconductor devices, such as IMPATT-, Gunn-, Tunnel-diodes and transistors have physics constrains not allowing their usage in THz frequency range. So, creation of a self-oscillator in THz frequency range is a challenge for nowadays technology.

In our earlier papers [1-5] we have discovered *a new Current instability* in reverse biased *asymmetric* ***p-n*** junction with impact ionization and show that this is the phenomenon promising for design of an efficient source of THz oscillations. At the same time, certain progress was shown in developments of THz sources using

Resonant-Tunneling Diodes (RTDs) as the promising candidates for room-temperature THz sources, which have been studying in [6,7]. In particular, oscillations having frequency up to 1.98 THz have been obtained at room temperature, and structures for higher frequency and high output power are being studied [8]. Moreover, some studies aiming toward several applications, such *as THz imaging, spectroscopy, wireless communications, etc. have been recently started* as well [9-15]. The application of RTD oscillators in *THz radar* has also been studied [16–19]. The sub-THz [20-21] and THz radar has the advantage that it can be used in harsh environments with poor optical visibility, due to their transparency for THz waves.

In the paper, theoretical results on a new current instability in reverse biased ***p-n*** junction with impact ionization are presented which is more suitable for generation of THz oscillations in comparison with conventional IMPATT diodes.

2. Current Instability in Self-Oscillatory Avalanche Diode

Spatial and temporal dynamics of current densities and electric built-in fields in the reverse biased multilayer semiconductor structures was studied within the frame of drift-diffusion model of semiconductors. The related system of partial differential equations consists of continuity equations for electron and hole currents densities and Poison's equation for electric built-in field, accounting both generation of the charge carriers via impact ionization and their recombination. For the abrupt ***p-n*** junctions, we developed a new efficient numerical method enabling simulation of spatial-temporal dynamics of currents and electric field in such semiconductor structures. Unlike known approaches we took into account mutual dependencies of the depleted layers widths on the generated electron-hole pairs, current densities and electric built-in fields. Using this method we studied variety of current self-oscillatory regimes as a consequence of the 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.

As a result of our theoretical investigations of current instabilities in reverse biased ***p-n*** junctions *the idea of Self-Oscillatory Avalanche Diode* (SOAD) has been suggested for design of a new *self-oscillator* for generation of microwave and THz electromagnetic oscillations [1-5]. Figure 1 shows schematic of the reverse biased asymmetric abrupt ***p-n*** junction, as the main part of the suggested SOAD.

The revealed current instability in reverse biased *asymmetric* ***p-n*** junction with impact ionization is promising for design of THz self-oscillatory sources [3,4]. This current instability takes place only in a ***p-n*** junction with *geometrical and/or doping asymmetries* of its ***p-*** and ***n-*** layers. In the basis of this current instability lays the following physical mechanism: the built-in electric field is compensated by the charges generated in the impact ionization layer (charge carriers avalanche), which lays inside the depletion layer of the inverse biased ***p-n*** junction. To reach an essential compensation of the built-in field, that may lead to decrease of the total static electric field inside the impact ionization layer, one has to provide a sufficiently high doping rate of impurities in the ***p-n*** junction. In turn, the 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 field, and so on. As an example, Figure 2 shows transients and current self-oscillations in GaAs reverse biased asymmetric ***p-n*** junction.

Further simulations were 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 the value of 10^{18} cm^{-3}.

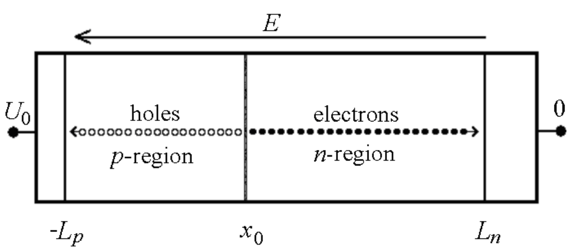


Figure 1. Schematic of the reverse biased asymmetric *p-n* junction

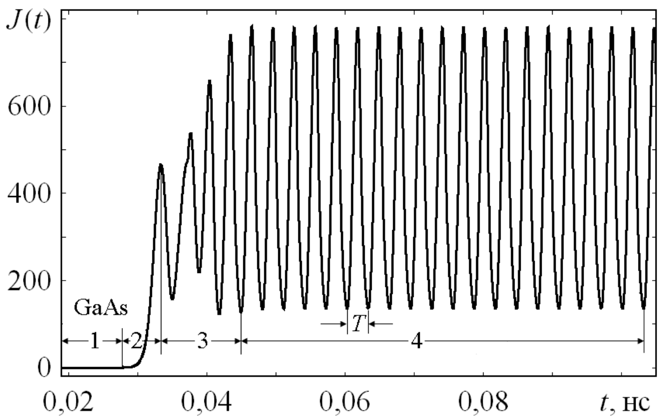


Figure 2. Current self-oscillations in GaAs reverse biased *p-n* junction

Figure 3 shows electron-current and hole-current densities across the asymmetric ***p-n*** junction at different time instances of self-oscillations which are numbered from 1 through 8. Distributions of the E-field across the ***p-n*** junction at different time instances are shown in Figure 4, numbered accordingly.

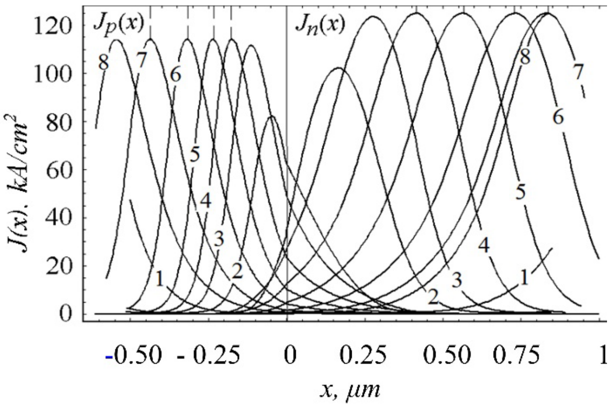


Figure 3. Electron- and hole-current densities across asymmetric *p-n* junction at different time instances numbered from 1 through 8.

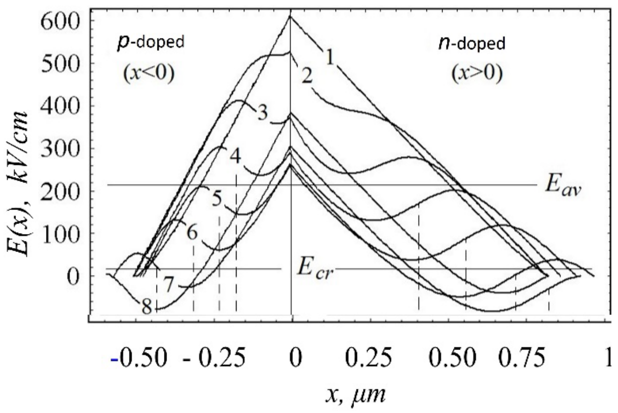


Figure 4. Distributions of built-in E-field across asymmetric *p-n* junction at the same time instances similarly numbered as in Figure 3.

One may readily trace the mutual dependence of the generated current densities and the built-in E-field in that type of current instability: when the currents decrease (increase) the E-fields increase (decrease), which was explained above. For justification of that current instability we did numerous computer simulations within the frame of the drift-diffusion model of classical semiconductor devices.

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.

The frequency of the current self-oscillations in *Si, Ge* and *GaAs* ***p-n*** junctions falls into the microwave and THz ranges and may be properly approximated by the following formula:

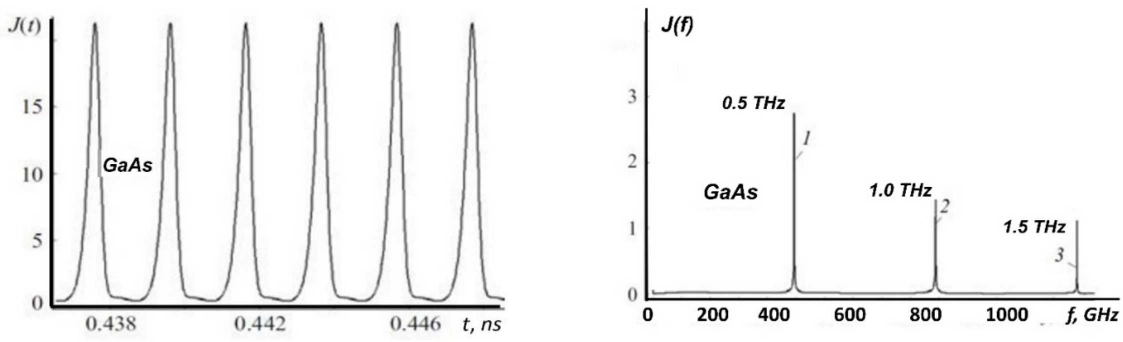
$$f = (v_{ns} + v_{ps})/2\bar{w}\delta_s,$$

where δ_s is matching coefficient which equals 0.515, 0.650, and 0.635 for *GaAs, Si,* and *Ge*, respectively.

Multiple simulations of self-oscillatory regimes in *Si, Ge* and *GaAs* ***p-n*** junctions were performed for a wide range of the impurity atoms concentrations, injection current densities, and reverse bias voltages. As an example, some results are presented in Figure 5. Figure 5a shows realization of self-oscillations of the hole-current density *J*(t), (kA/cm^2) in the depletion $\boldsymbol{p}^+$–region of GaAs $\boldsymbol{p}^+\boldsymbol{n}$ junction for $U/U_{av} = 2.05$; $N_a = 2\ 10^{17} cm^{-3}$; $N_d = 2\ 10^{16} cm^{-3}$. As it is seen, the current self-oscillations are of relaxation type, i.e. are highly anharmonic.

Figure 5b displays the Fourier spectrum *J*(*f*) of these current self-oscillations of the avalanche hole-current density shown in Figure 5a. Spectral lines *1*, *2*, and *3* represent the first, second and third harmonics, respectively, of the relaxation current self-oscillations:

$$f_1 = 0.5\,THz, f_2 = 1.0\,THz;\ f_3 = 1.5\,THz\,.$$



a) **b)**

Figure 5. Reverse biased asymmetric GaAs *p*$^+$-*n* junction:

a) *steady-state relaxation self-oscillations*; **b)** *Fourier spectrum of the relaxation oscillations of Figure 5a*

In *GaAs* Self-Oscillatory Avalanche Diode with higher doping rate the fourth harmonic frequency reaches **2.55 THz** in the relaxation oscillatory mode.

It has been shown that for typical dimensions of ***p***- and ***n***-areas and reverse biased voltages **< *100 V*** the suggested device may generate self-oscillations having the first Fourier harmonic from ***0.01 THz*** up to ***0.5 THz***. When highly anharmonic regime is achieved (Figure 4a), the second and third harmonics with frequencies ***1 THz*** and ***1.5 THz***, respectively, have a comparable output power (Figure 4b).

Along with regular current instability we revealed chaotic current instabilities, when studying reverse biased multilayered semiconductor structures [1]. In chaotic oscillatory regimes, the wideband and ultrawideband random THz signals are generated with power spectral density width from ***2 GHz*** up to ~***20 GHz***.

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 signals with high frequency up to ***1 THz*** [22]. 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 various frequency bands [22]. 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 equation in structures with lamped active devices to the initial problems for time-delay nonlinear equation of difference and difference-differential type [23, 24].

Conclusions

The discovered current instability in reverse biased ***p-n*** junction may be used as the basis for design of a new type of sub-THz and THz semiconductor self-oscillators, named as Self-Oscillatory Avalanche Diodes – SOAD, which is a promising approach for development of a compact, low-voltage THz devices. These devices may be used for design of advanced THz sources for radar, communications, imaging and sensor systems.

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