# ELECTRICAL GENERATION OF TERAHERTZ CURRENT OSCILLATIONS IN BALLISTIC DEVICES

*Alexander N. Korshak* and *Vladimir V. Mitin*

Wayne State University, Detroit, MI 48202, USA

## Abstract

A theoretical study of ballistic transport of current carriers with negative differential effective mass is presented. A symmetric double-heterostructure p-type quantum well is considered as a realistic system with current carriers (holes) which have the required dispersion relation. A ballistic current of quantized holes in a short doped p-type quantum well generates current oscillations. This generation is a result of a negative effective mass part in the hole dispersion relation. An oscillation frequency is in the terahertz range and depends on the inner parameters of the diode structure with quantum well base. It is approximately determined by a carrier transit time through the diode base. GaAs quantum wells of about 8 nm width, 0.1÷0.3 $\mu$m length, and $10^{11}$ cm$^{-2}$ acceptor doping may be used for generation in the range of 0.5÷1.5 THz.

## 1 General principle of generation

We consider current carriers with a special non-parabolic dispersion relation. The peculiarity of this dispersion is that the differential effective mass becomes negative in a some region of wavevectors, and it is positive outside of this region. Figure 1 shows an example of the dispersion relation, $\varepsilon$, with a negative differential effective mass (NEM) part. A group velocity, $v = \partial\varepsilon/\partial p$, and an inverse effective mass, $1/m = \partial^2\varepsilon/\partial p^2$, as the functions of wavevector, $k = p/\hbar$, are shown in Fig. 1, b, c. We do not assume that the velocity of the carriers is negative for a positive momentum as would be in the case of a negative mass everywhere. Negative differential effective mass means that an increment in momentum results in a decrement in velocity.

A ballistic plasma with current carriers having negative differential effective mass (NEM-carriers) is convectively unstable [1]. It can be easely confirmed by finding a spectrum of excitation in the quasineutral plasma with carriers having negative mass, $m_c$. For a frequency of excitation $\omega$ with a wavevector $k$ we have

$$\omega = v_c k \pm i\omega_c,$$

where $v_c$ is a velocity of the NEM-carriers, $\omega_c^2 = e^2 n_0/\kappa_d |m_c|$ is the plasma frequency for the NEM-carriers, $n_0$ is a concentration of ions, and $\kappa_d$ is a dielectric constant. We see that the frequency is complex with a positive imaginary part. This means that any fluctuation in the plasma is increasing, and therefore, the homogeneous state of the quasineutral plasma with the NEM-carriers is unstable.

## 2 NEM carriers

To implement this instability for generation we should find a system with the required dispersion relation for current carriers. We have considered three different systems which allow the carrier dispersion relations with a NEM part. They are: 1) electrons in an asymmetrical double quantum wells formed by materials with considerably different electron masses, or electrons in a composite ΓX-quantum well [2], 2) holes in uniaxially compressed semiconductor [3], and 3) holes in a heterostructure quantum well [4]. The later system seems to be the most realistic for fabrication of the proposed generator.

Quantization of holes in a double heterostructure quantum well is a reason of mixing of light and heavy hole states. Spin-orbit interaction between them results in a complicated dispersion relation shown in Fig. 2, and the lowest subband of the quantized hole spectrum is exactly what we need. A position of the NEM part depends on the well width and depth. Therefore changing a well width or choosing another material system allow one to obtain the hole dispersion with a desired position of the NEM part.

## 3 Ballistic diode

To exploit the instability associated with the NEM of quantized holes we should form a quasineutral ballistic plasma region with NEM-holes as current carriers. The simplest way is to accelerate holes ballistically to the energy where they have NEM. In the ballistic diode with a p-type quantum well as a base holes enter into the base from the heavily doped anode, are accelerated in the electric field, and finally reach another contact (cathode) with energy $eV_D$, where $V_D$ is a voltage across the diode base. It is important that no scattering occurs in the diode base and the energy of these carriers is exactly determined by the potential difference between the initial and final states. The distribution function of the ballistic carriers is overstretched in the current direction and the energy width of the ballistic beam is determined by the Fermi energy of the injected carriers. Therefore, the Fermi energy should not be greater than the energy width of the NEM part in the hole dispersion relation.

Here we consider a ballistic diode with parallel equipotential plates — cathode and anode, which are connected by current-conducting channels of length $L$. These channels form a spatial periodic system with a spatial period $a$.

A solution of a stationary problem of space charge limited ballistic currents for holes which have a dispersion relation with a NEM part shows that the electric field distribution in the diode base is nonuniform [5]. The diode base can be divided into three parts: a dipole space charge region near the cathode with comparatively light holes which have energy below the energy of the NEM part, then a wide quasineutral region with moving NEM-carriers (NEM-region), and the second dipole space charge region near anode with comparatively heavy carriers which have energy higher than the energy of the NEM part. The widest region is the quasineutral NEM-region where the electric field is small. Stationary current-voltage characteristics show saturation of the current as a function of the voltage $V_D$ in the voltage interval when this NEM-region exists in the base. The voltage, when the current saturation begins, corresponds to the energy of the NEM part. Instability in the NEM-plasma results in the current oscillations [6] which are accompanied by the plasma waves propagating in the NEM-region. The oscillation frequency is determined by the transit time, and this frequency is in the terahertz range for submicron ballistic structures. Numerical simulations indicate that in most cases spectrum of these oscillations is characterized by the main frequency which depends on the applied voltage. Figure 3 shows a relation between the current oscillations with a single main frequency and the dispersion relation of the carriers. The oscillation regime appears in the voltage interval where the current saturation for stationary characteristics would be expected. For a long diode base when the NEM–region becomes sufficiently long the oscillation spectrum becomes complicated due to excitation of modes with higher frequencies.

## 4 Ballistic regime

Ballistic transport regime in the base of the diode holds if a carrier transit time, $\tau_{tr}$, through the base is sufficiently smaller than a mean scattering time, $\tau_{sc}$. Since the transit time determines a frequency of the oscillations we get a fundamental restriction for the lowest attainable frequency of oscillations. It is determined by the scattering time in the diode base, $f_{min} = 1/\tau_{sc}$. So to obtain oscillations with the frequency 1 THz we have to guarantee scattering time longer than 1 ps.

Let us make some simple estimations to determine the ballistic length which corresponds to that time. To estimate the mean velocity of the carriers in the base, we take the velocity of the NEM-carriers. For the particular dispersion relation in Fig. 1, this velocity is about 0.1 $\mu$m/ps or $10^7$ cm/s and the ballistic length must be greater than 0.1 $\mu$m.

**How can the ballistic length be increased?** To have a scattering time in the range of a few picoseconds carriers should not reach the energy of the optical phonon. For GaAs this energy is about 36 meV. Therefore the energy position of the NEM part in the hole dispersion relation is chosen below the optical phonon energy, near 20 meV, to obtain oscillations in a sufficiently long voltage interval.

Below the optical phonon energy the main contribution to the scattering comes from ionized impurity scattering. To decrease this contribution one usually uses a modulation doping with spacer width of about 10 nm or greater. Reported hole mobilities in p-type GaAs quantum wells on <311>A-GaAs substrates are greater than 100,000 cm$^2$/Vs for helium temperatures. This mobility seems to provide the scattering time of longer than 5 ps.

## 5 Characteristics of the oscillation regime

**Frequency.** For a sufficiently high doping the length of the space charge region is small and the length of the NEM region is approximately equal to the base length. Oscillations of about 1 THz are expected in the 0.1 $\mu$m base for the velocity of the NEM carriers of $10^7$ cm/s. For 0.2 $\mu$m base the oscillation frequency is decreased to 500 GHz.

To increase the frequency of the oscillations we have to decrease the base length. When shortening the base length becomes of the order of the width of the space charge region, $\Lambda$. For a bulk ballistic diode this width is given by

$$\Lambda = v_c \frac{\pi}{e} \sqrt{\frac{m\kappa}{n_0}},$$

where $m$ is a positive effective mass near the bottom of the subband. For bulk doping of $10^{17}$ $cm^{-3}$ this width can be estimated as 40 nm. For a shorter base the NEM region shrink and no oscillations occurs. The base length when the oscillations disappear is about 60 nm for that doping. Increased doping shortens the width of the space charge region and allows oscillations for shorter base lengths with higher oscillation frequencies.

When the base doping is increased, the Fermi energy of the injected carriers (or the cathode doping) should be increased to hold a space charge limited current regime in the ballistic diode. This regime is necessary because it provides a nonuniform electric field distribution in the diode base with a long quasineutral NEM-region. An increased Fermi energy causes an increased energy width of the ballistic beam. If this width becomes greater than the energy width of the NEM part in the hole dispersion relation the oscillations weaken because only a part of the carriers has the NEM while the other part has a positive mass. The current carried by the holes with the positive mass shorten the oscillations. For the given dispersion relation and for the given injection scheme we have a fundamental limitation for the maximum attainable frequency of about 2 THz. This frequency is expected for the base of 60 nm length, $3 \cdot 10^{11}$ $cm^{-2}$ doping, and 12 meV Fermi energy of injected carriers. The dispersion is supposed to have the NEM part near 20 meV.

To get frequencies higher than 10 THz we have to shorten the base length to 30 nm and to increase the energy of NEM carriers to 0.1 eV. In this case even optical phonon scattering with scattering time of about 0.2 ps will not prevent the ballistic transport in the base. The velocity of the NEM carriers is then about $2.5 \cdot 10^{7}$ cm/s and the ballistic length is about 50 nm. We have to sufficiently increase doping to shorten the space charge region to about 20 nm. Therefore, the doping in the range of $(2 \div 3) \cdot 10^{12}$ $cm^{-2}$ is required.

**Output power.** The input power of the ballistic diode with p-GaAs/AlAs quantum wells of ~ 9 nm width is about 5 mW $cm^{-1}$. The efficiency and output power of the generator depend on the load resistance. Our estimates show that the output power is expected to be about $5 \cdot 10^{-5}$ W $cm^{-1}$ and the efficiency — about 1 %, when the load resistance is equal to 0.2 $\Omega$ cm. If the length of the structure in the third direction is about 200 $\mu$m (the in-plane size is 0.1 × 200 $\mu m^2$) the microwave power is about 1 $\mu$W per quantum well at the load resistance of 10 $\Omega$. We can significantly increase the output using multiwell structures grown layer by layer.

**Required structure.** For our goals we need a symmetrical p-type double heterostructure rectangular quantum well with sharp and flat sidewalls. The well width should be smaller than 9 nm. Symmetrical (double-side) modulation doping of $\geq 10^{11}$ $cm^{-2}$ is required to reduce ionized impurity scattering. To provide a sufficient depth of the hole quantum well one has to use heterostructures: 1) GaAs/$Al_xGa_{1-x}$As with $x > 0.6$ (up to $x = 1.0$), or 2) $In_{0.53}Ga_{0.47}$As/InP. In the case of GaAs/AlGaAs-structure, higher hole mobilities are observed for the structures grown on < 311 > A-GaAs-substrates with Si as acceptor. Multiwell structures are desirable to increase output power. Parallel $p^+$-contacts to the quantum well are regions enriched by diffusion or implantation. They have to be spaced by 0.1÷0.5 $\mu$m or even smaller.

# References

1. Z. S. Gribnikov, A. N. Korshak. Semiconductors **28**, 1445 (1994).
2. Z. S. Gribnikov, A. N. Korshak, N. Z. Vagidov. J. Appl. Phys. **80**, 5799 (1996).
3. N. Z. Vagidov, Z. S. Gribnikov, A. N. Korshak. Semiconductors **31**, 150 (1997).
4. A. N. Korshak, *et al.*, Phys. Stat. Sol. (b), **204**, 80 (1997); A. N. Korshak, *et al.*, Microelectronic Eng., accepted (1998); Z. S. Gribnikov, *et al.*, ICPS-23 Proc.,

Berlin, **4**, 3287 (1996).

5. N.Z.Vagidov, Z.S.Gribnikov, A.N.Korshak. Semiconductors **29**, 286 (1995).
6. N. Z. Vagidov, Z. S. Gribnikov, A. N. Korshak. Pis'ma ZhETF, **61**, 38 (1995).

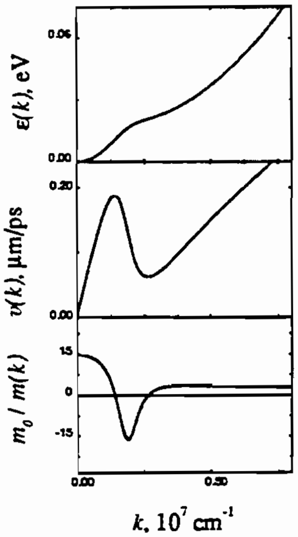

**Figure 1.** Dispersion relation, $\varepsilon(k)$, with differential negative effective mass domain, velocity, $v(k)$, and differential effective mass, $m_0 / m(k)$.

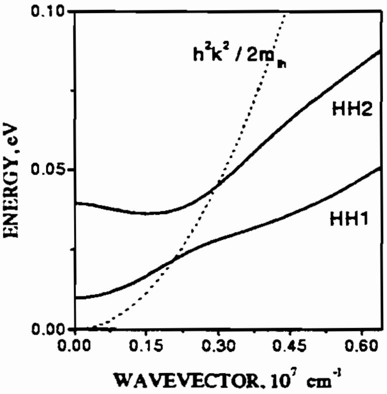

**Figure 2.** Quantized hole spectra for p-GaAs/AlAs quantum well of 8 nm.

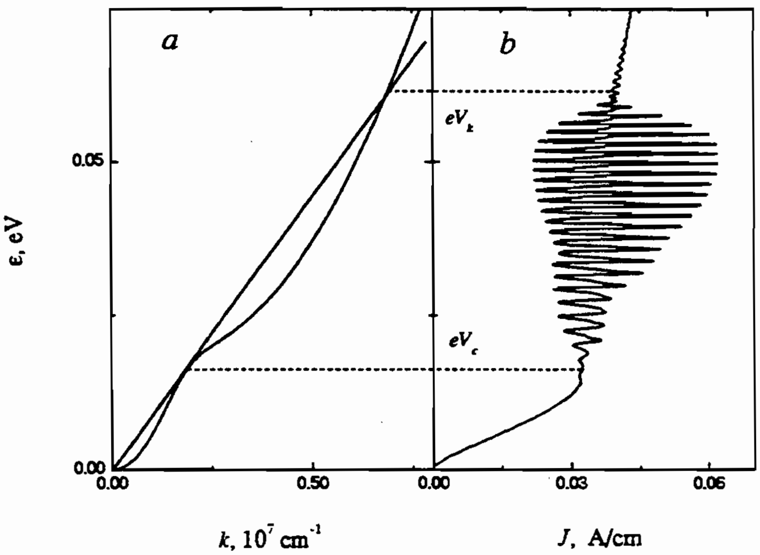

**Figure 3.** Dispersion relation, $\varepsilon(k)$, and corresponding current oscillations as a function of applied voltage $eV_D = \varepsilon$ for p-GaAs QW of 0.5 μm length, 9 nm width, and $2 \cdot 10^{10}$ cm$^{-2}$ doping.