Heterostructure Equivalence of Step-Recovery Diodes for Ballistic and Diffusive Electron Resonance - a New Concept for THz Signal Generation

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Abstract—**A heterostructure equivalent to the well-known step recovery diode principle, arranged as a double structure gives a new nonlinear device for highly efficient harmonic THz signal generation. Like in the case of step recovery diodes, these devices exhibit promising performance especially for the generation of higher order harmonics. Theoretical and experimental results will be presented.**

I. Introduction And Background

The well-known step recovery effect of pn-junctions can now be realized in a highly improved way by transferring the basic principle to heterojunctions. In fact, two barriers opposing each other via a narrow-gap semiconductor such as AlGaAs/GaAs/AlGaAs or InAlAs/InGaAs/InAlAs with a suitable n-doping can be considered as two step recovery diode junctions in opposition, which operate without any dc bias requirement.

There are two types of structurization. The first one has a localized mobile electron source in front of the barriers, as shown by Fig. 1. Here a suitable doping is employed.

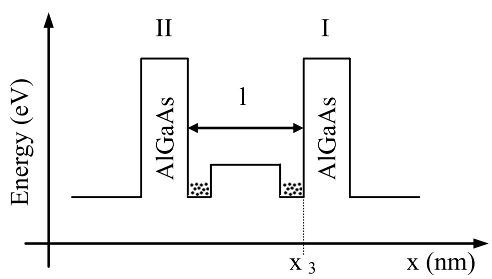

Fig. 1. Schematic illustration of the energy band profile for enhanced THz harmonic output.

When the fundamental wave voltage is applied, the electrons from the higher potential trough travel towards the lower potential barrier, where they are reflected at the position x_3. It appears that all electrons are reflected at exactly x_3 independent of their energies. Depending on the length l either diffusive effects occurs or ballistic transport takes place. In the latter case the value of l needs to be smaller than about 200 nm. The electrons reflected at barrier I can be expected to travel in the potentially upward direction. If the fundamental wave is then starting to decrease, the bunch of ballistic electrons can experience a second reflection at barrier II. After one half period of the fundamental wave, also the charge in front of barrier I starts to join this ballistic reflection system. Instead of an undoped transit space it is possible to use also a structure as shown by Fig. 2. In our case of ballistic transport, InGaAs material is highly favoured due to the mean free path of electrons which exceeds 100 nm in this material at room temperature [1].

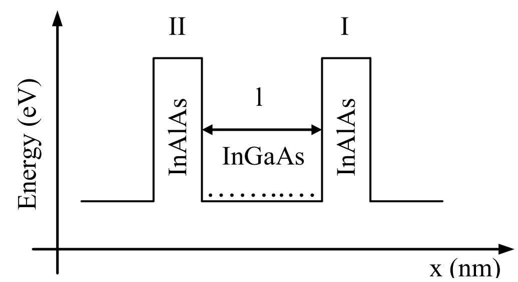

Fig. 2. Double barrier heterojunction structure

II. Basic Design Concepts

The input signal in the fundamental wave therefore transfers all the electrons of the n-GaAs region towards one of the heterojunction barriers. Here, the electrons are reflected which may locally result in a negative current. In any case, when the electron-cloud reflection occurs, a very sharp drop in the current takes place in line with the understanding of the old idea of a p-i-n step recovery diode. In such old structures such a drop in current was caused by the total disappearance of the charge carriers.

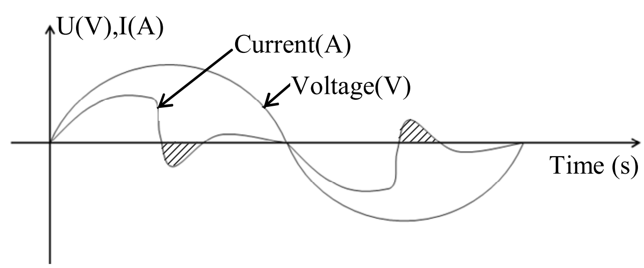

Fig. 3. Variation of the output harmonic signal as function of the input RF versus time.

Here, however, the charge carrier (normally only electrons) is totally reflected. The current signal is then transferred capacitively via displacement currents to the outside electrodes of this heterojunction structure (see Fig. 3 regarding some possibility of efficient harmonic generation). It is therefore needed to design this component appropriately for maximum harmonic output.

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III. MONTE-CARLO SIMULATION RESULTS

A semi-classical self-consistent ensemble Monte Carlo (MC) model is used to simulate the electron dynamic in the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ double-heterojunction structures. The details of the MC model used in this work has been reported in Ref. [2]. The material parameters of $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ are taken from Ref.[2] and [3], respectively. The band offset [4] between the Γ-valleys of $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ is taken as 0.5 eV. In the model, abrupt heterojunctions are assumed and the interface perfectly reflects the impinging electron, where its wave vector component k_z, normal to the interface is changed to $-k_z$.

This ensemble MC simulator self-consistently coupled with a Poisson solver, where the potential profile between the contact layers was derived at a time step of 1 fs. The Poisson equation was solved on a uniform spatial mesh with spacing of 1 nm. Any LC-resonances due to the external geometry of the device are neglected to evaluate the electron reflection resonance only. The simulations were started with more than 10^5 particles representing the thermal equilibrium electrons in the well. Simulations were performed by taking a one-dimensional geometry at 300 K for doping concentrations of $n = 1\times10^{16}$ cm^{-3} in the well of 120 nm width within two undoped $In_{0.53}Ga_{0.47}As$ spacers of 3 nm and followed by the undoped $In_{0.52}Al_{0.48}As$ barrier layers of 15 nm. Electrons in the potential well of such a dimension behave primarily according to classical concepts. The instantaneous current density, $J(t)$, in the device was evaluated based on the well known Ramo's theorem [5]. The spectra of the THz radiation is obtained from the Fourier analysis of the time-dependent intensity of radiation based on the autocorrelation function defined as

$$I(\tau) \propto \int_{-\infty}^{+\infty} E_{rad}(t) E_{rad}(t-\tau) dt , \qquad (1)$$

where $E_{rad} \propto dJ(t)/dt$ and τ is the delay time.

The simulated current density under the excitation of a sinusoidal signal at 250 GHz with amplitude of 1.2 V is shown in Fig. 4. In the first half period, electrons are accelerated by the external electric field to the opposing barrier, indicated by a large transient current. At the heterointerface, these electrons are reflected and travel to the opposite energy barrier against the externally applied field. As a result the current decreases to a negative value as more electrons are reflected with time. Eventually the velocity of the reflected electrons is reduced to zero and reversed in the direction by the applied electric field, and then accelerating toward the same barrier again. In this way the current resonates as electrons bounce backward and forward for a given time. The transit times between reflections are of sub-picoseconds so that the transport is mainly ballistic. This resonance phenomenon dies down after a few numbers of periods as the coherency of electron transport is destroyed by scattering. The reversed bias repeats this phenomenon at the opposite barrier. The corresponding electron dynamic in the well as a function of position and time in the first cycle were computed in terms of the electron density and the mean electron velocity, jointly with the related electric field profiles. The large positive and negative mean electron velocities recorded in the well at both positive and negative peak biases confirmed that electrons in the well travel quasi-ballistically to reach such high speeds before reflected from the heterointerfaces.

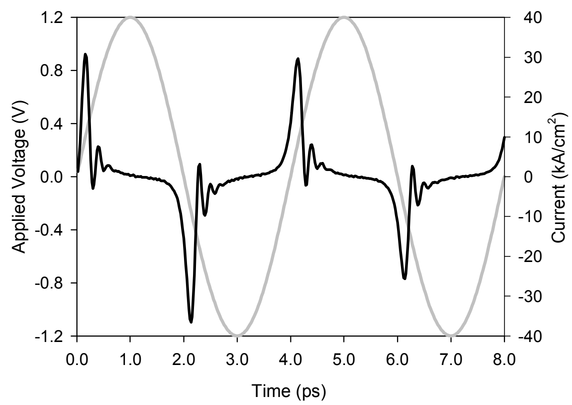

Fig. 4. Temporal evolution of current density in response to sinusoidal signal at 250 GHz with amplitude of 1.2 V

The radiated field due to the current oscillation in the double barrier heterostructure is shown in figure 5(a) and its corresponding Fourier spectrum of THz radiation is shown in figure 5(b) with frequencies ranging from 0.1-5 THz. The calculated autocorrelation intensity is presented in the inset of the figure. This study clearly demonstrates that a double barrier heterojunction structure with well width of ballistic electron transport length can be used to generated THz signals.

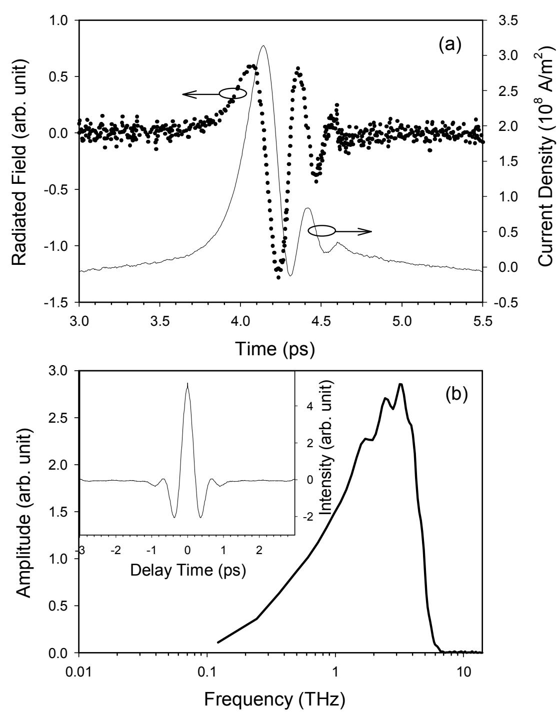

Fig. 5. (a) Current waveform and its radiated field (b) The corresponding amplitude of THz radiation calculated from the Fourier transform of the autocorrelation intensity shown in the inset.

IV. EXPERIMENTAL APPROACH

The structure of Fig.1 with l = 75 nm was experimentally studied and harmonic efficiency of 25 % was theoretically obtained. Theory shows that the ultimate efficiency is 3 times higher than that of a corresponding Hetero Barrier Varactor.

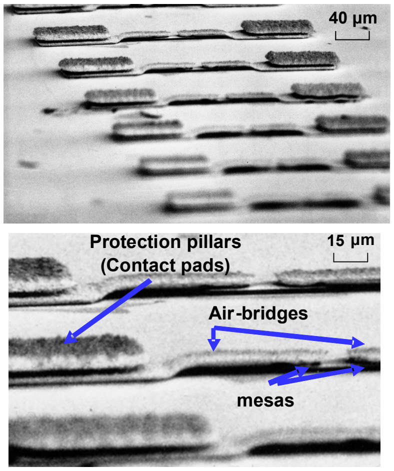

Fig. 6. SEM picture of 2 fabricated devices connected in planar approach (up) and a close approach with the protection pillars, air-bridges and mesas (down).

In figure 6 we can see an example of the fabricated devices used during the high frequency measurements. With the total dimensions of 160 µm (L) x 30 µm (W) x 60 µm (H), and a mesa diameter of 10 µm, the optimum design revealed a capacitance modulation ratio C_{max}/C_{min} of approximately 3.54 at ±8V, an series resistance R_S of approximately 7Ω and the cut-off frequency f_c of 2THz.

The measured characteristics of the planar devices are showing a good symmetry from the origin point, a sharp drop-down and a good agreement with the simulations.

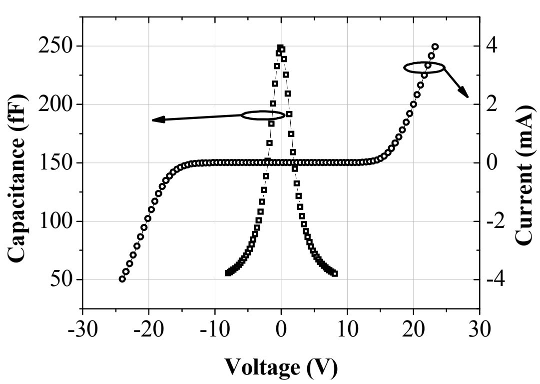

Fig. 7. The current-voltage (I-V) and capacitance-voltage (C-V) measurements of the planar devices at room temperature. The diameter of the mesa is 10 µm. The measurements were performed between maximum ±25V and at a centre frequency of 1GHz.

The cut-off frequency of the new proposed devices was estimated to exceed 1 THz. Therefore, and for ease of manufacturing and measurement, frequency multiplication from W-Band frequencies (75 – 110 GHz) to approximately 300 GHz was chosen as a first step to validate the theoretically found results. The fabrication approach included a planar tripler circuit on a quartz substrate and the growth and dicing of two of the structures shown in Fig. 1, connected in series configuration. The device was flip-chip mounted on a 50 µm thick substrate with the microstrip circuitry developed and simulatively optimized for sufficient impedance match and low transmission losses. Figure 8 shows a microscopic view of the planar circuitry.

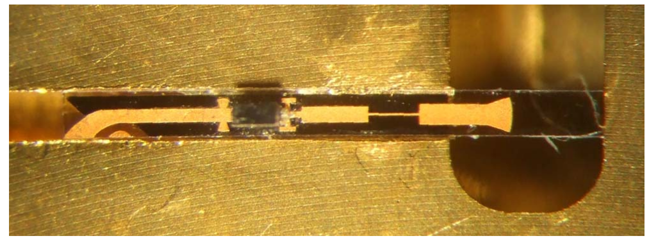
Fig. 8. Microscope picture of the fabricated circuitry with the device mounted on a gap of the microstrip line.

Using WR-03 and WR-10 waveguides as input and output in split-block technology provided a fully waveguide based tripler setup with the possibility of TRL-calibration and error correction. A geometrical model of the device was used within full 3D field simulation software to include parasitic effects of the device structure. When feeding the input waveguide of the resulting split-block with a frequency of 102 GHz the output signal around 306 GHz was clearly detectable proving that the theoretical approaches hold. The measured efficiency, however, did not reach the simulated values up to now. Higher input power and improved circuit design with tuneable elements are expected to raise the efficiency for tripling operation to higher values. The simulation and modelling efforts as well as measurement results are described in more detail in [6].

CONCLUSIONS

It was demonstrated that old concepts of p/n junction devices can be converted into heterostructure equivalences with good advantage. The new idea of a heterojunction electron/charge swing promises to give enhanced harmonic conversion efficiency, as was demonstrated by this paper.

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