Theory and Design of Smith-Purcell Semiconductor THz Sources

Don Smith[a], Alexey Belyanin[a]
[a] Department of Physics and Astronomy, Texas A&M University, College Station TX USA

***Abstract*— We recently proposed a room-temperature semiconductor THz source that operates via Smith-Purcell radiation of Gunn domains. We present simulation results of an optimized narrowband design that generates 0.4mW at 0.3THz and 1.1uW at 2.5THz and discuss preliminary results towards the design of a room-temperature chip-scale THz synthesizer.**

I. Introduction And Background

We recently proposed the concept of a compact room-temperature semiconductor THz source that radiates via the Smith-Purcell effect[1], as illustrated in Figure 1.

A metallic grating of period P is fabricated on a spacer layer of thickness b deposited on the surface of a planar Gunn diode in dipole-transit mode. The Gunn domain is a space-charge dipole moving through the semiconductor at a material- and bias-dependent velocity v.[2,3] The moving space charge induces image charge on the teeth of the metallic grating, which radiates via the Smith-Purcell effect.[4,5] The frequency f of the radiation is equal to the ratio of the domain velocity v and the grating period P. For typical domain velocities of order 10^5 m/s, micron to submicron grating period yield frequencies in the range 0.3-2.5THz.

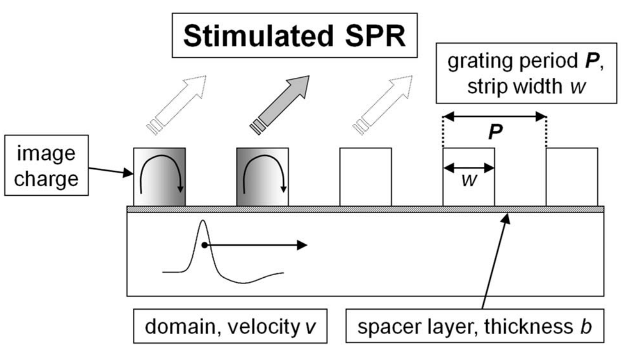

Fig. 1. Proposed Smith-Purcell THz source: The domain of a planar Gunn diode induces oscillating image charge on a metallic grating, which generates Smith-Purcell radiation.

A simple analytic model for the radiated electric field was derived, based on replacing real metal in close proximity to a point charge by an ideal conductor. Using this induced surface charge density allows the straightforward calculation of the electric field created by a point charge in the device. The electric field for an arbitrary charge distribution is then readily obtained by numerical superposition.

The theoretical basis of the Gunn effect is very well-understood and we apply the numerical 'equal-areas' method to published material data to estimate domain profiles under different device conditions.[6] Analytic approximations of the numerical domains are used as input to Comsol® time-domain simulations of the device, which agree well with analytic results. This basic toolkit provides a robust means to explore the design space of the device concept.

II. Results

After initial investigation of several materials, we decided to focus on InN despite its current immaturity. GaN-on-Si development is rapid, but the lower applied field associated with InN gives it the promise of being the next high-frequency material of choice.[4,5]

A simulated 100um-wide bare InN device generates on order of tens of nW at 1THz and behaves as an ideal point dipole. The small size (<1um) of the dipole makes the bare device an inefficient radiator. Power can be increased by creating arrays of bare devices. The power of an in-phase array of bare devices is found to vary as the square of the number of devices N in the array.

Connecting a single bare device to a half-wave dipole antenna boosts radiated power significantly without the need to manage the phases of many array elements. The consolidated results for a study of 34 InN devices are shown in Figure 2. The study consisted of devices with five different applied bias conditions (domain shapes) with several grating periods at each bias condition. Maximum power was 0.4mW at 0.3THz, power at the maximum frequency of 2.5THz was 1.1uW.

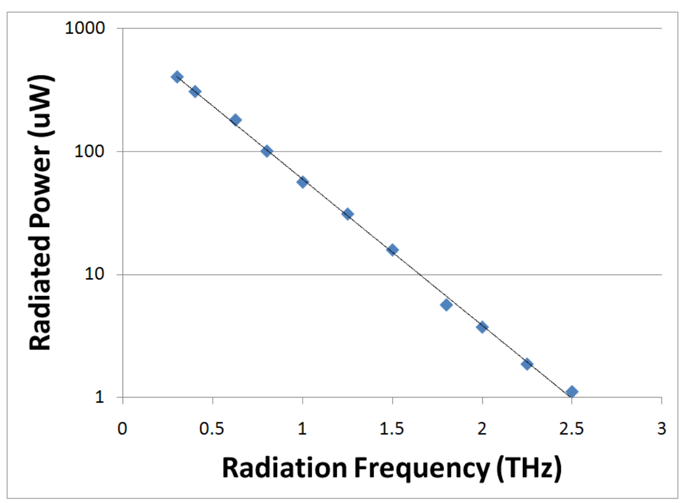

Fig. 2. Combined simulation results for 34 InN devices with half-wave dipole antennas. Power varies as $\sim 1/f^3$ from 0.4mW at 0.3THz to 1.1uW at 2.5THz.

Several key factors determine the output power of the device: The amount of charge in the domain, the ratio of the domain width to the grating period P, the duty factor of the grating, and the thickness of the spacer layer b. A general

design tradeoff for Gunn diodes is that increasing the applied bias to the device increases the amount of charge in the domain but lowers its drift velocity and widens its spatial extent. Therefore in designing devices of the type we propose, the optimal grating geometry is coupled to the expected shape of the Gunn domain. The devices operate best when the grating period is of the same order as the domain width. The power rolls off strongly for narrow periods and weakly for wide periods.

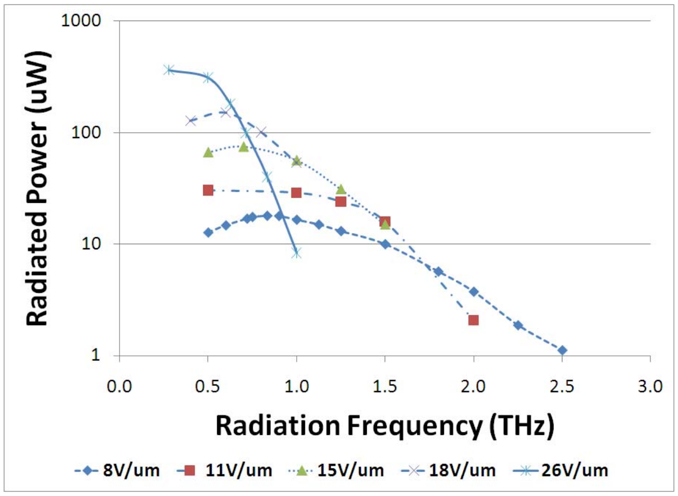

Fig. 3. Results for all InN dipole-antenna devices show faster frequency rolloff for the high-bias (wider domain) devices.

The devices discussed thus far all utilize a grating with a uniform period along the entire length of the Gunn diode. Thus the radiation is very narrowband in character, and the only spectral flexibility with the fixed-period grating is in the amount of second and third harmonic present in the power spectrum of the device. Purer first-harmonic operation is achieved either by increasing the thickness of the spacer layer b or by using a grating period P ~30% smaller than the domain width – which both come at the expense of total output power.

We do not attempt to presuppose and design to all possible THz applications, but certainly multi-frequency and wideband applications may be well-served by compact room-temperature semiconductor sources. To this end, we have completed an initial investigation into variable-period grating designs. We began with a bare device (no antenna) with a thin spacer layer thickness b to enhance second-harmonic content. A variable-period grating was added to split the power spectrum into multiple peaks. The grating design utilizes constant gap width between grating teeth, and the distance between each tooth was set by a geometric sequence of ratio 0.975. This resulted in tooth spacing between 0.45um and 0.32um.

The time-domain electric field data collected during the Comsol® simulations was replicated several times to approximate continuous-wave operation. Power spectra were calculated by performing fast Fourier transforms (FFT) of the time-domain electric field data. Comparison of the fixed-period to variable-period device is shown in Figure 4.

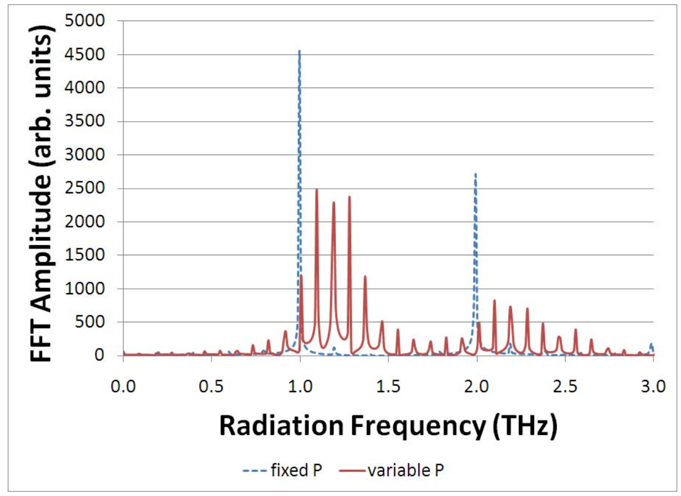

Fig. 4. Power spectra of a fixed and variable-period device.

The spacing of the frequency peaks can be tailored to an application by changing the spacing ratio, and the voltage-tunability of the Gunn diode allows an additional degree of freedom in moving the spectrum. Simulation of wideband antenna designs for these devices is planned and will be presented elsewhere. It is envisioned that a simple IC consisting of several independent devices with different grating designs, mounted in-package with a control ASIC, form a very reasonable basis for a room-temperature, solid-state THz waveform synthesizer.

III. CONCLUSION

We proposed the concept of a room-temperature semiconductor THz source that operates via Smith-Purcell radiation of Gunn domains. Optimization of a half-wave dipole antenna allows simulated InN devices to radiate 0.4mW to 1.1uW of power over the 0.3-2.5THz range. Power varies with radiation frequency f approximately as $1/f^3$, and significant design flexibility exists to tailor the device concept to different THz applications.

We have demonstrated that the use of a variable-period grating readily enables multi-frequency operation. The results indicate that the combination of variable-period grating and intrinsic voltage tuning provide a solid technological basis for a simple, low-cost THz synthesizer IC.

REFERENCES

[1] D. Smith, A. Belyanin, "Room-temperature semiconductor coherent Smith-Purcell THz sources", Appl. Phys. Lett. vol. 98, 2011, pp. 063501-1-3.
[2] M. Shur, GaAs Devices and Circuits (Plenum Press, New York, 1987).
[3] S. M. Sze and K. K. Ng, Physics of Semiconductor Devices, 3rd ed. (Wiley-Interscience, Hoboken, N.J., 2007).
[4] S.J. Smith, E. M. Purcell, "Visible light from localized surface charges moving across a grating", Phys. Rev. vol. 92, 1953, p1069.
[5] J. H. Brownell, J. Walsh, "Spontaneous Smith-Purcell radiation described through induced surface currents",Phys. Rev. E, vol 57, 1998, pp.1075-1080.
[6] P. Butcher and W. Fawcett, "Stable domain propagation in the Gunn effect", Brit. J. Appl. Phys. 17(11), 1966, pp. 1425–1432.
[7] V. M. Polyakov, F. Schwierz, "Low-field electron mobility in wurtzite InN," Appl. Phys. Lett. 88(3), 2006, pp. 032101–1–3.
[8] J. Wu, "When group-III nitrides go infrared: New properties and perspectives," J. Appl. Phys. 106(1), 2009, pp. 011101–28.