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Room-temperature semiconductor coherent Smith–Purcell terahertz sources

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We propose a room-temperature semiconductor source of coherent narrowband Smith–Purcell radiation (SPR) in the low-to-mid terahertz range. The device is a planar Gunn diode with a metallic grating deposited near the drift region. Stimulated SPR is generated as domains move under the grating. Radiation frequency is determined by the domain velocity and grating period—it is not transit-time limited. The approach is photolithographically tunable, readily scales to arrays, and is compatible with any planar Gunn technology. Integration with a planar antenna improves radiation efficiency and enables far-field optimization. We develop an analytic theory of the devices which agrees well with simulations. Results indicate that this method may achieve technologically relevant power density levels and warrants experimental investigation. © *2011 American Institute of Physics*. [doi:10.1063/1.3554364]

Smith and Purcell focused a dc vacuum electron beam across a metallic grating and observed electromagnetic radiation. The wavelength was found to depend on the reduced electron velocity $\beta = v/c$, observation angle θ, and grating period P according to[1]

$$\lambda_{SPR} = P[\beta^{-1} - \cos\theta]. \quad (1)$$

Spontaneous (single-electron) Smith–Purcell radiation (SPR) power is very low, but a bunched beam causes many electrons to coherently radiate. This *stimulated* SPR power increases as the square of the number of charges in the bunch and is observed to be many orders of magnitude larger than spontaneous SPR.[2] Vacuum SPR devices (orotrons) have been known for many years and self-consistently accumulate electrons in an electrodynamic structure in the decelerating phase of a slow electromagnetic wave. Orotron development is active, with modern orotrons recently reported at 0.41 THz.[3,4]

Spontaneous SPR has been observed from semiconductors at liquid helium temperatures,[5] but short scattering length (<1 μm) prevents slow-wave electron bunching. The Gunn effect, however, provides robust room-temperature electron bunching in semiconductors and highly doped devices have submicron domain widths.

We propose that a grating fabricated near the surface of a planar Gunn diode (Fig. 1) produces a solid-state stimulated SPR device. To the best of our knowledge this is a novel realization of the Smith–Purcell effect. The radiation frequency of the proposed device scales with the grating period P as v/P [cf. Eq. (1)]. Submicron grating period and domain velocity of order 10^5 m/s yields low terahertz frequency.

Notch-doped InP planar Gunn diodes have been fabricated for many years.[6] The planar geometry allows a grating to be fabricated close to the domain. Shoji demonstrated that electrodes on the surface of GaAs Gunn diodes produce predictable current wave forms, and Gunn measured domains and their velocity dependence on the electric field using a capacitive probe technique.[7,8]

We consider the case of a uniformly propagating dipole domain using the equal-area method for an arbitrary velocity-field characteristic.[9–11] We find reasonable agreement between our calculations of domain sizes and velocities and the Monte Carlo results for InP and GaN.[12,13] InN is a rapidly developing device material with lower threshold field and higher carrier velocities than GaN.[14] We use a recent velocity-field characteristic[15] to calculate InN domains (Fig. 2) to investigate the SPR performance of potential InN Gunn diodes.

A modal theory of SPR was given by Toraldo di Francia in 1960. In 1973, van den Berg extended the theory and solved specific cases. Goldstein *et al.* experimentally verified the theory in 1997.[16–18] The technical difficulty of the general theory urges the use of a simplified SPR model whenever possible. Early workers pictured an oscillating electric dipole perpendicular to the grating plane with a dipole moment that varies sinusoidally in time at the Smith–Purcell frequency $f = v/P$,

$$p_z = qb\cos\left(\frac{2\pi v}{P}\right)t. \quad (2)$$

This model predicted higher SPR power than was experimentally observed.[19] Neglecting the longitudinal component of the dipole moment predicts *minimum* field intensity normal to the grating plane, but we observe that the intensity is actually *maximum* normal to the grating.

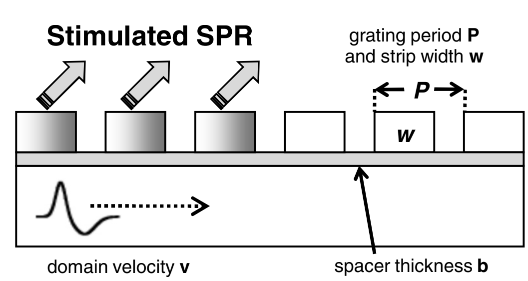

FIG. 1. Proposed Smith–Purcell terahertz semiconductor device.

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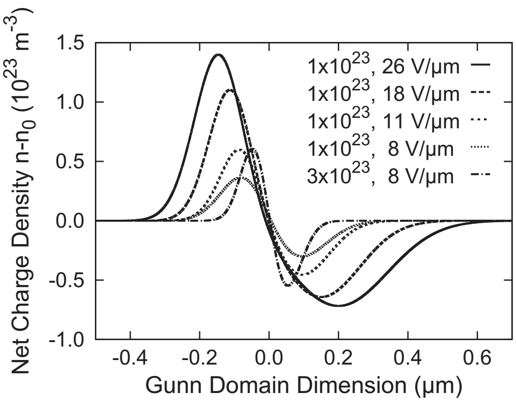

FIG. 2. Domains calculated for the InN device simulations. Numbers on the plot give the average doping in m^{-3} and electric field for different devices.

We have developed a simple analytical model of the Smith–Purcell radiator which predicts the field intensity and SPR power of our two-dimensional (2D) numerical simulations. Consider the case of a point charge q moving with velocity v along the x-axis. An infinitely thin perfectly conducting grating of infinite width in the y-direction placed a small z-distance b above the moving point charge. The grating has strips of width w and spatial period P in the x-direction. The entire device has length L.

Assume that the observation distance $\boldsymbol{r}$ is much greater than the dimension $\boldsymbol{r}'$ of the device and that ρ is the image charge induced on an infinite grounded plane conductor by a point charge q,

$$\rho(\boldsymbol{r}',t) = -\left(\frac{qb}{2\pi}\right)\frac{\delta(z'-b)}{[(x'-vt)^2+y'^2+z'^2]^{3/2}}. \tag{3}$$

The transverse component of the dipole moment is zero. The longitudinal and normal components are readily found from direct integration,

$$p_x = -qbF(r,t) = -qb\left(\frac{1}{\pi}\right)\sum_{n=0}^{L/P-1} \times\left[\frac{1}{2}\ln\left(\frac{\left\{1+\left[\frac{vt}{b}-\left(\frac{vr}{cb}+\frac{nP}{b}+\frac{w}{b}\right)\right]^2\right\}}{\left\{1+\left[\frac{vt}{b}-\left(\frac{vr}{cb}+\frac{nP}{b}\right)\right]^2\right\}}\right)\right], \tag{4}$$

$$p_z = qbG(r,t) = qb\left(\frac{1}{\pi}\right)\sum_{n=0}^{L/P-1}\left\{\tan^{-1}\left[\frac{vt}{b}-\left(\frac{vr}{cb}+\frac{nP}{b}\right)\right] - \tan^{-1}\left[\frac{vt}{b}-\left(\frac{vr}{cb}+\frac{nP}{b}+\frac{w}{b}\right)\right]\right\}. \tag{5}$$

The longitudinal component $F(t)$ exhibits sharp oscillations when the charge moves between the edges of the grating strips. In the limit of very small b, $G(t)$ approximates a series of rectangular unit pulses with period P/v and width w/v. $F(t)$, $G(t)$, and their parametric plot showing rotation of the dipole are given in Fig. 3.

The Larmor formula gives the SPR power,

$$P_{\rm SPR} = \left(\frac{2}{3}\right)\left(\frac{1}{4\pi\epsilon_0}\right)\left(\frac{\langle\ddot{\boldsymbol{p}}\rangle^2}{c^3}\right). \tag{6}$$

We used the 2D time-dependent mode of Comsol's® RF Module for simulations. Models consisted of the grating, the spacer layer, the Gunn drift region, and a circular air box three free-space wavelengths in diameter. Since the small rotating dipole is an inefficient radiator, an integrated antenna was added to several models.

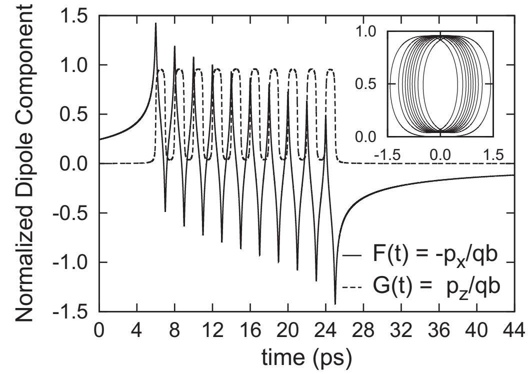

FIG. 3. Parametric plot (inset) showing the rotating dipole.

A detailed report and analysis of all the results will be presented elsewhere. A set of simulations was run to measure SPR power as a function of the spacer layer thickness b. SPR power decreases exponentially as charge-grating separation increases. Vertical thickness of the grating has minimal effect on the power. Duty factor w/P of the grating does affect the far-field pattern and output power. In our simulations we chose $w/P=0.8$, roughly corresponding to maximum power. We took $b=100$ Å, drift region thickness of 140 nm, and device length $L=5$ μm in all simulations. Since the radiation frequency is determined by the grating period P and not by the device length L, the latter may vary depending on the application.

Figure 4 shows SPR power versus frequency for bare devices. The calculated domains (Fig. 2) were run with different grating periods in the range from 1.6 to 0.18 μm, corresponding to different frequencies according to $f=v/P$. Domain velocity depends on the electric field; the 26, 18, 11, and 8 V/μm electric fields in the figure correspond to 2.5×10^5, 3×10^5, 4×10^5, and 4.5×10^5 m/s velocities in InN. The SPR power decreases as frequency is increased and the domain size becomes much larger than the grating period. At the lowest frequencies (widest periods), the power also decays slightly. Many bare devices generate between 0.1 and 1.0 nW/μm in the low terahertz range.

The power dependence on the device geometry and domain parameters can be seen more clearly by rearranging the

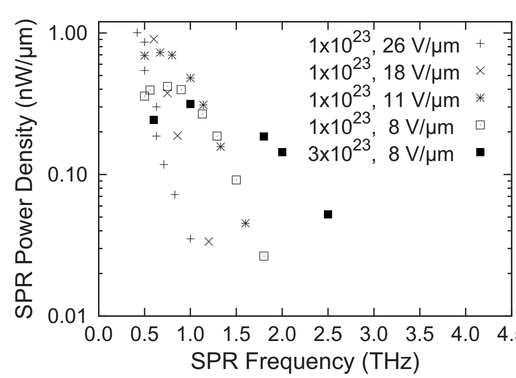

FIG. 4. SPR power per unit length in y-direction vs frequency for 49 simulated bare InN devices.

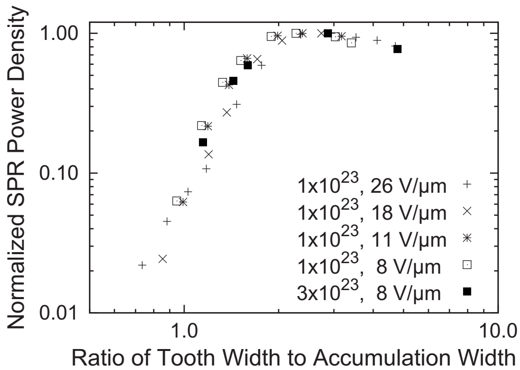

FIG. 5. Universal curve for the 49 devices in Fig. 4. The tooth width w is equal to $0.8P$.

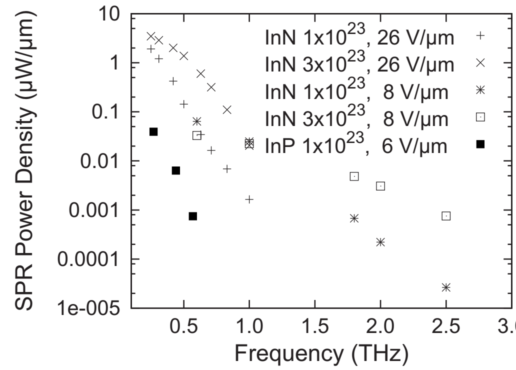

FIG. 6. Integrated antennas significantly boost SPR power.

data in Fig. 4. We normalize the power of each device to its maximum and plot the normalized power versus the ratio of tooth width w to domain width. There is some ambiguity as to how to define the domain width. We found that using the accumulation width (where net charge is greater than 1% of the nominal device doping) results in the "universal curve" shown in Fig. 5. The SPR power is maximized when the grating tooth is two to three times wider than the accumulation width and decreases rapidly when the domain is much wider than the grating period. We added simple nonoptimized half-wavelength antennas to the devices to achieve higher output power. The effect was significant, as seen in Fig. 6. The high-bias InN device reached 3.5 μW/μm at 0.25 THz, while the low-bias device generated 3.1 nW/μm at 2.0 THz.

We have proposed a concept and design for a novel room-temperature monolithic semiconductor device that emits coherent narrowband terahertz radiation via the stimulated Smith–Purcell effect. Analytic calculations and simulations agree that technologically relevant SPR power levels in the frequency band from 0.2 to 2.5 THz may be achieved. The devices are robust, simple in design, based on mature fabrication technology, scalable to arrays, and photolithographically tunable. We conclude that the approach warrants experimental investigation.

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