SAND2013-2101C

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Tunable Plasmonic Crystals Induced from a Two Dimensional Electron Gas

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The City University of New York

APS March Meeting, Session C22, March 18th 2013

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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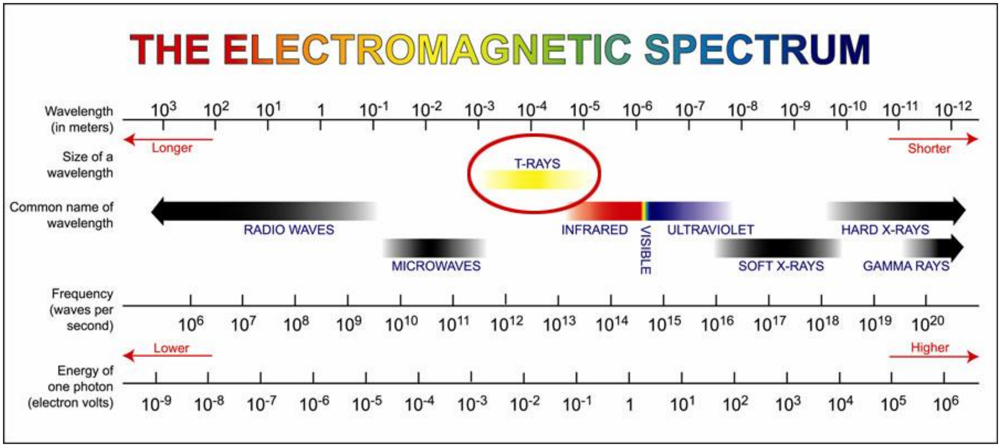
2D Plasmons in the Terahertz Band

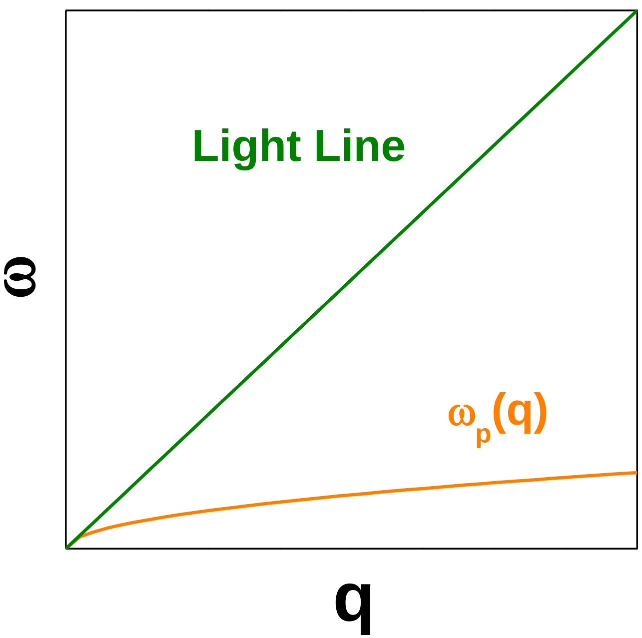


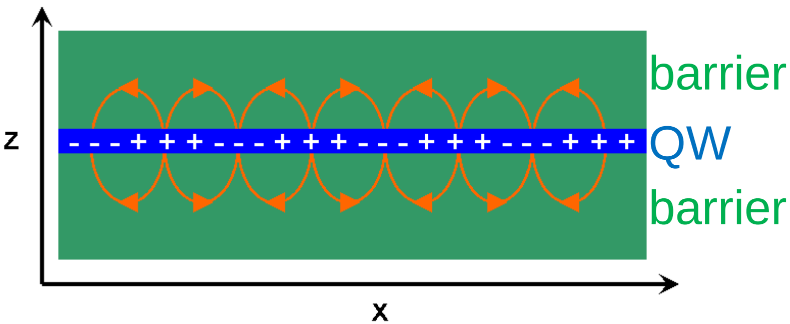
<u>Electronics</u>: *RC* limited bandwidth

<u>Photonics</u>: *kT* limited below 1 THz

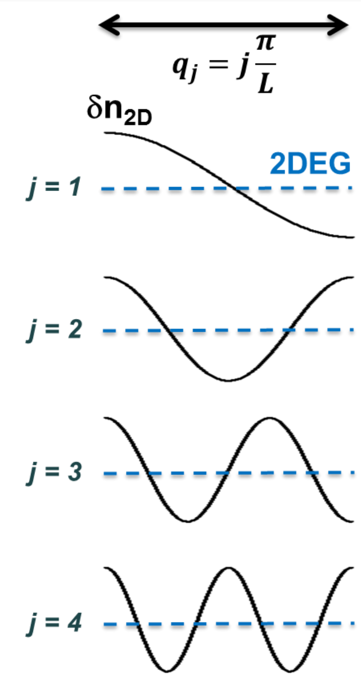
<u>Plasmonics</u>: ωτ cutoff

from *http://web.njit.edu/~barat/RBB_research.html*



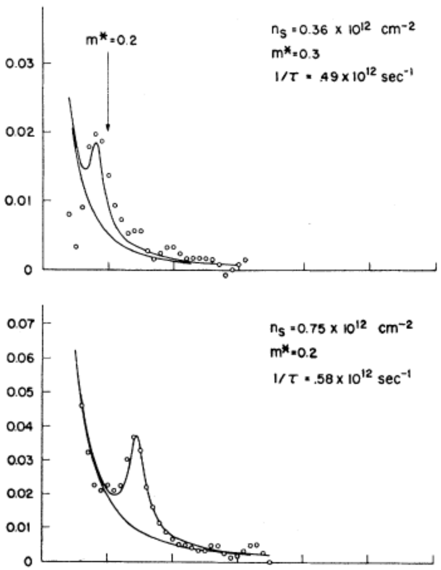


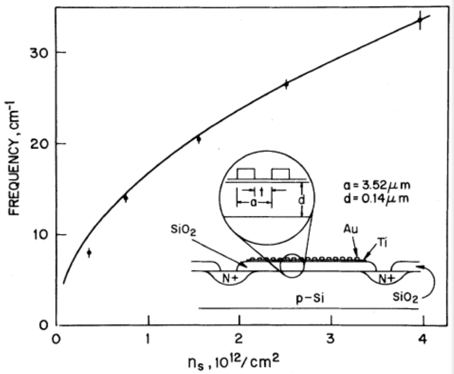
$$\omega_p = \sqrt{\frac{n_{2D} e^2 q_j}{2\epsilon m^*}}$$



THz 2D Plasmonic Systems

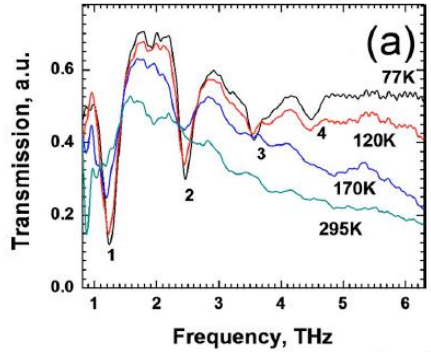
Grating Gated Si MOSFETs

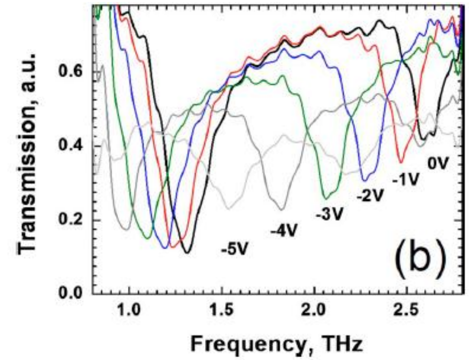


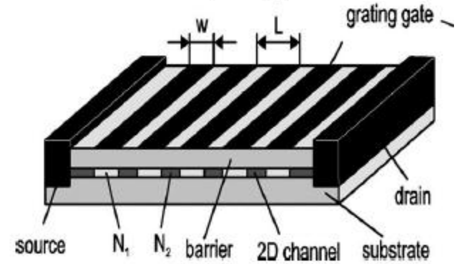


S. J. Allen et. al., *PRL* **38**, 980 (1977)

Grating Gated III-V HEMTs

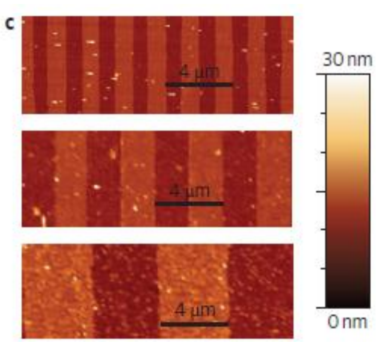


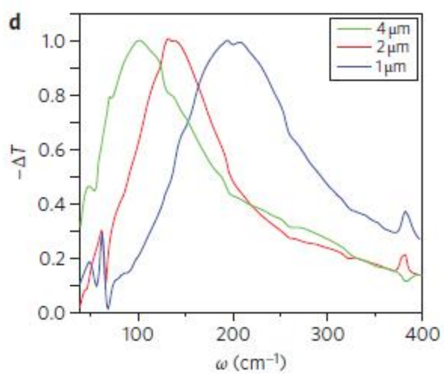


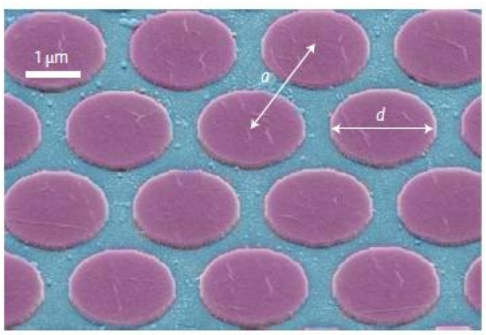


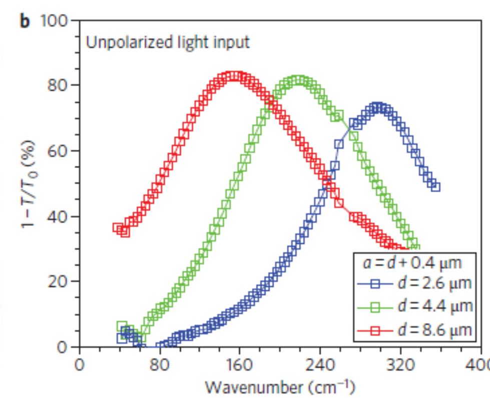
A. V. Muravjov, et. al., *APL* **96**, 042105 (2010)

Periodic Graphene Structures





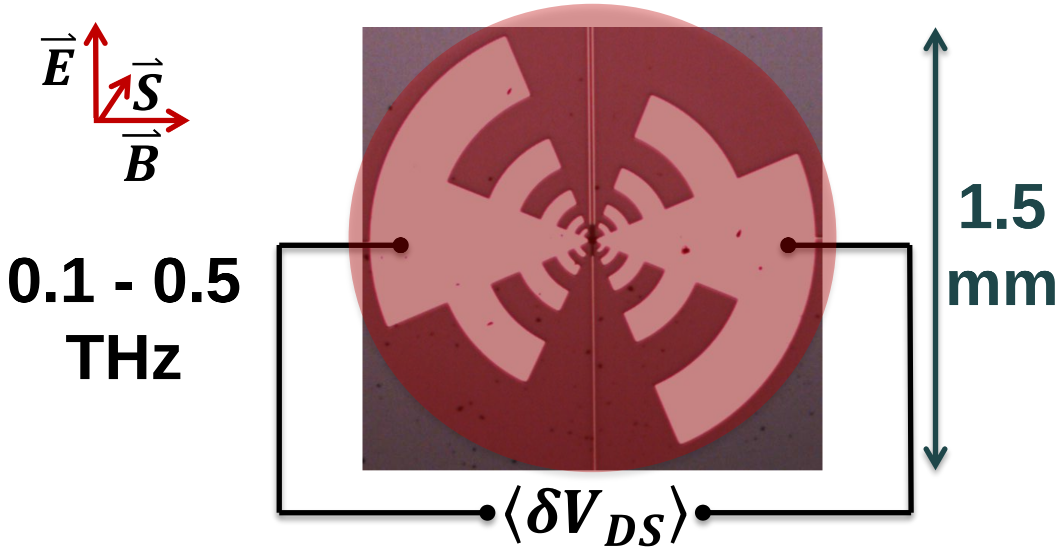


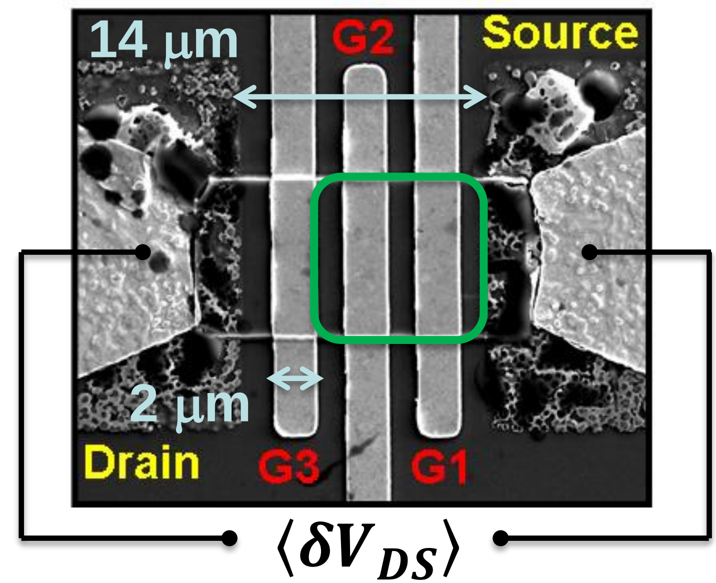


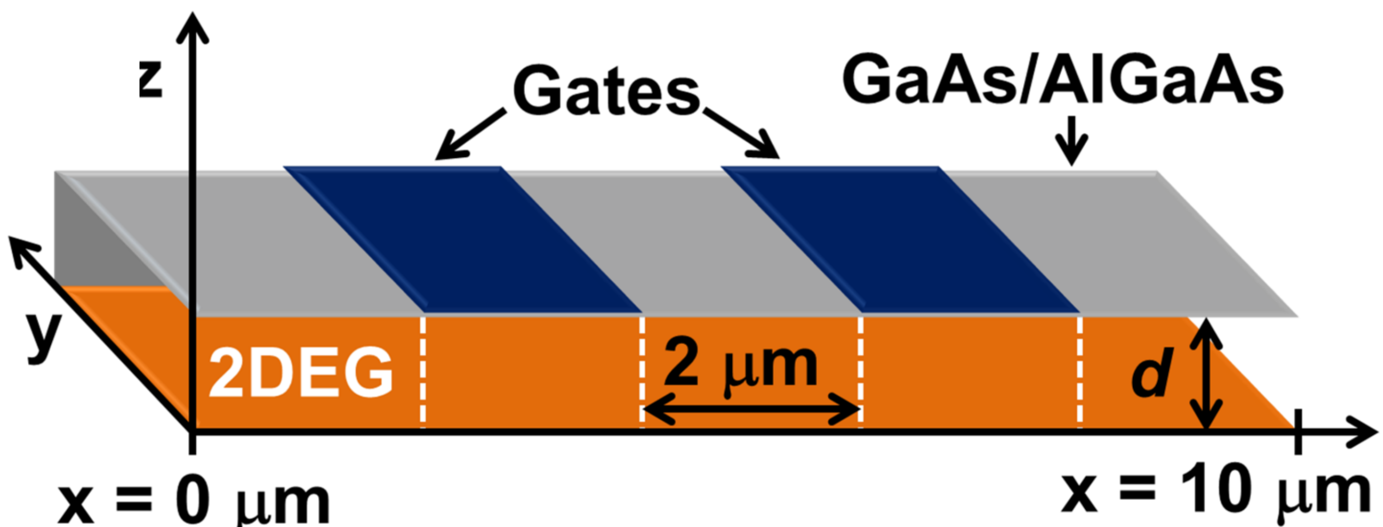
L. Ju et. al., *Nat. Nano.* **6**, 630 (2011)

H. Yan et. al., *Nat. Nano.* **7**, 330 (2012)

Antenna Coupled 2DEG Structures

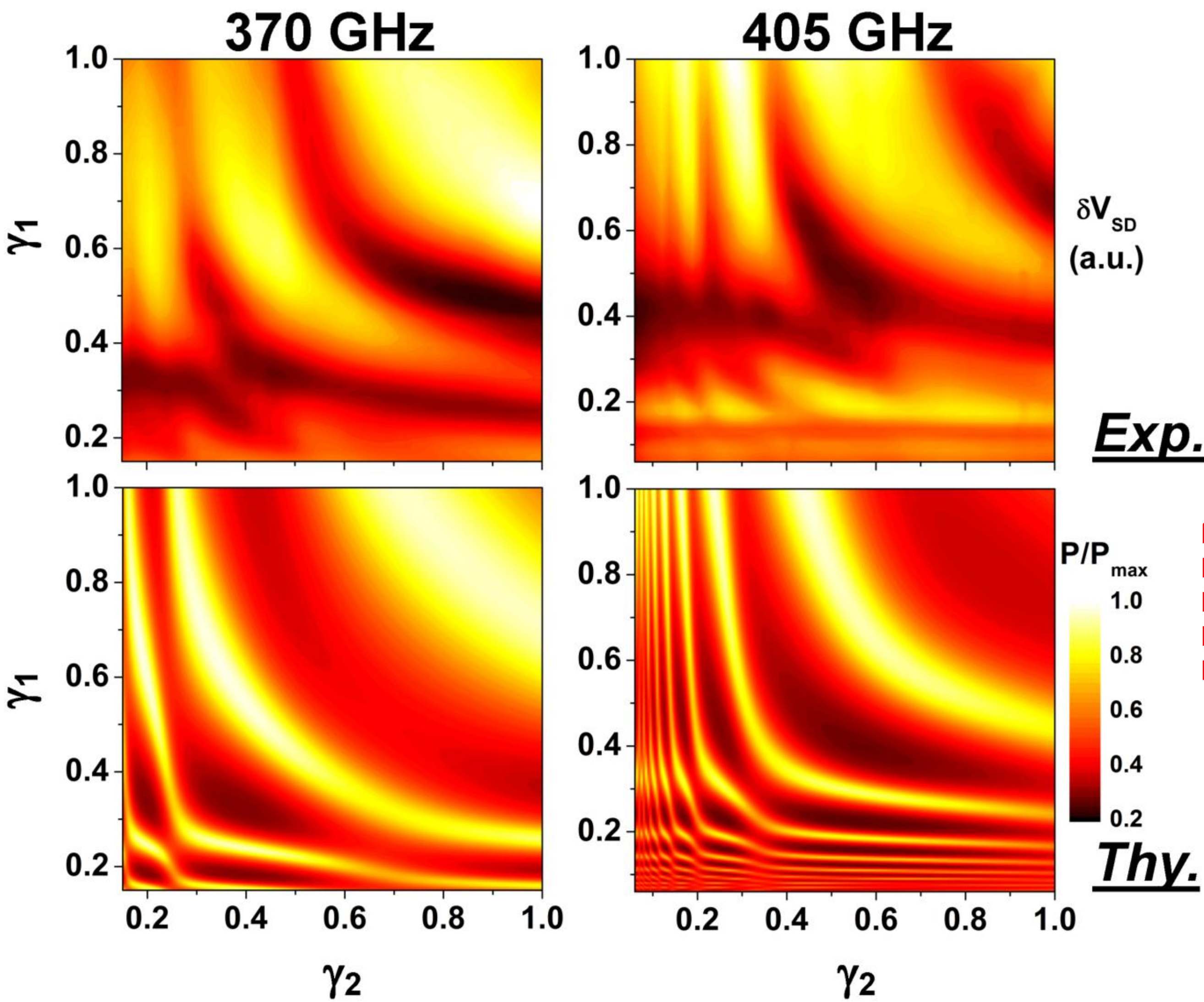


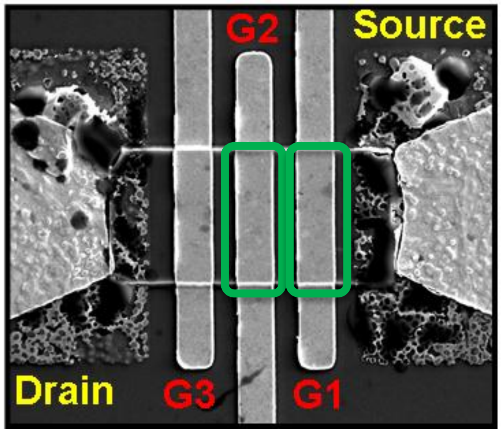




G. C. Dyer *et. al.*, *PRL* **109**, 126803 (2012) & G. C. Dyer *et. al.*, *APL* **100**, 083506 (2012)

Coherent Sub-Cavity Interaction



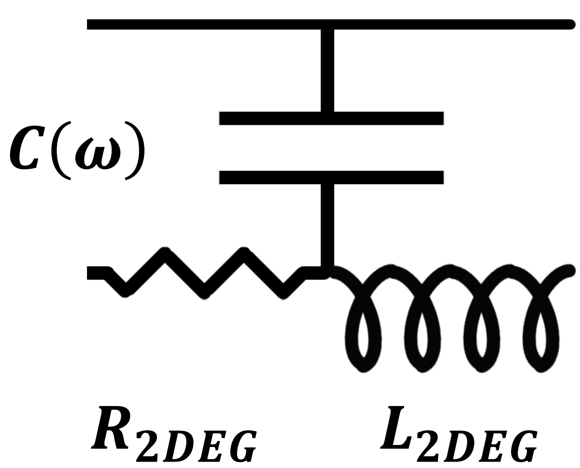


$$\gamma_{1,2} = \frac{V_{th} - V_{G1,G2}}{V_{th}}$$

Strongly coupled 2D plasmonic resonators

G. C. Dyer *et. al.*, *PRL* **109**, 126803 (2012)

Generalized Plasmonic TL Model



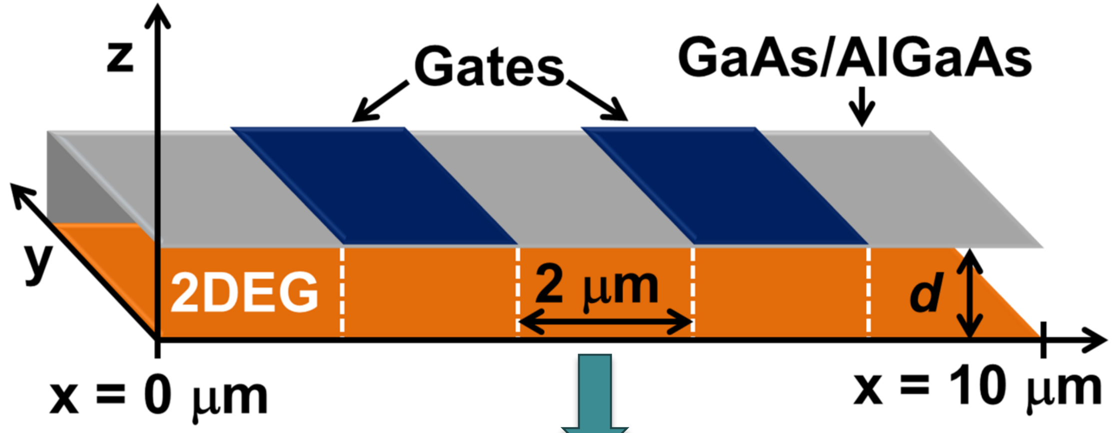
$$C(\omega) = W\epsilon q(1 + \coth[qd])$$
$$R_{2DEG} = \frac{m^*}{\tau e^2 n_{2D} W}$$
$$L_{2DEG} = \tau R_{2DEG}$$

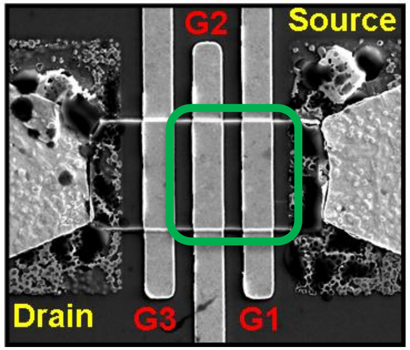
$$\tilde{V}(x) = \Phi(x, 0)$$
$$\tilde{I}(x) = I(x)\xi(\omega, d)$$

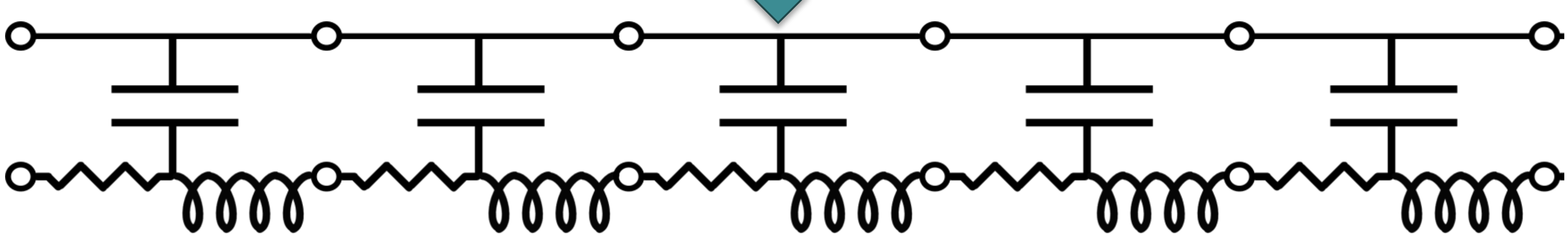
where: $\xi(\omega, d) = 1 - \frac{q\left(1 - e^{-2q'd}\cos[2q''d]\right)}{2q'\left(1 - e^{-2q^*d}\right)} + \frac{q\, e^{-2q'd}\sin[2q''d]}{2q''\left(1 - e^{-2q^*d}\right)}$

G. C. Dyer *et. al.*, *PRL* **109**, 126803 (2012) & G. R. Aizin and G. C. Dyer, *PRB* **86**, 235316 (2012)

Discretized Plasmonic TL







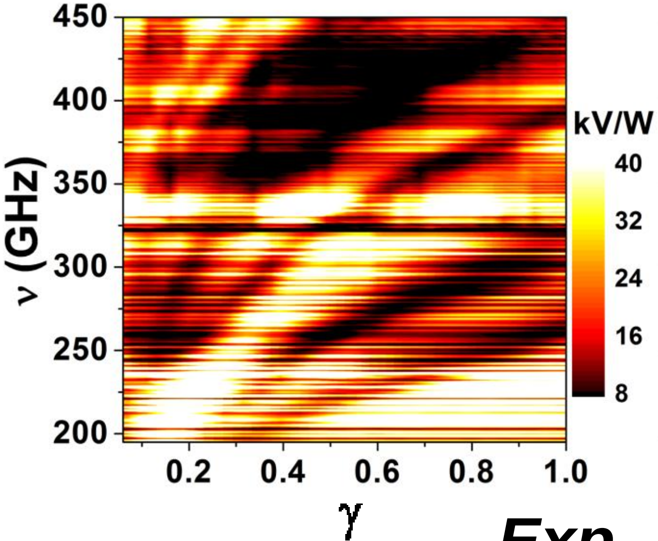
$$\tilde{Z}_0 = \frac{1}{\xi(\omega,d)}\sqrt{\frac{R_{2DEG} + i\omega L_{2DEG}}{i\omega C(\omega)}}$$

$$iq = \sqrt{i\omega C(\omega)(R_{2DEG} + i\omega L_{2DEG})}$$

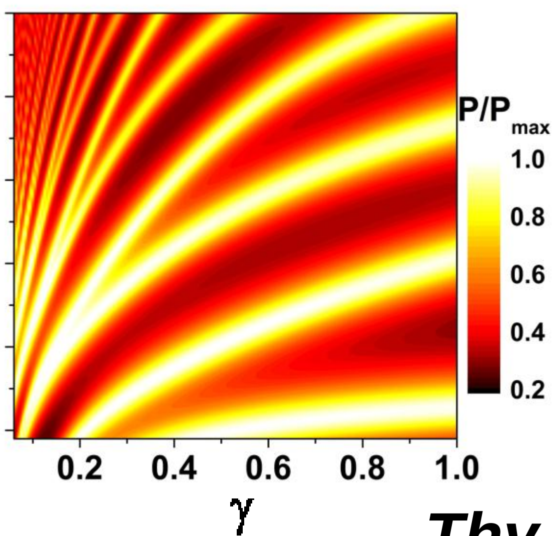
where: $\xi(\omega,d) = 1 - \frac{q\left(1-e^{-2q'd}\cos[2q''d]\right)}{2q'\left(1-e^{-2q^*d}\right)} + \frac{q\,e^{-2q'd}\sin[2q''d]}{2q''\left(1-e^{-2q^*d}\right)}$

G. C. Dyer *et. al.*, *PRL* **109**, 126803 (2012) & G. R. Aizin and G. C. Dyer, *PRB* **86**, 235316 (2012)

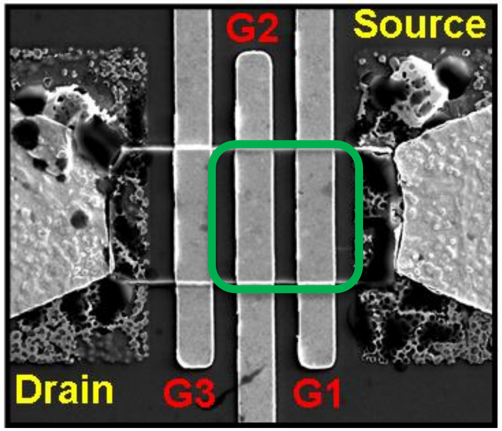
Incipient Finite Plasmonic Crystal



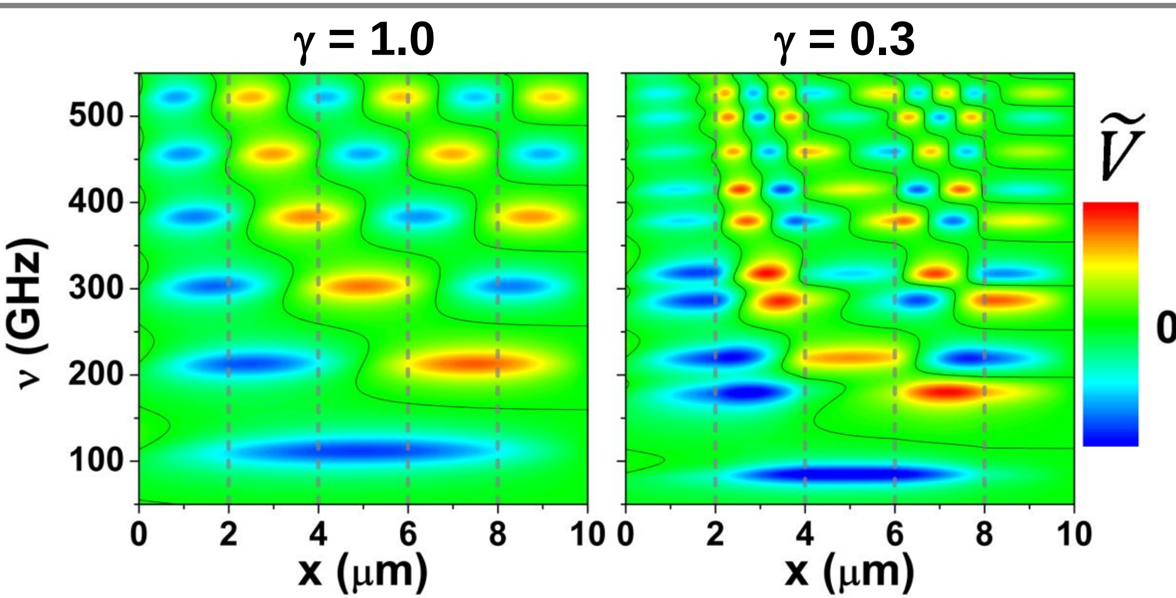
Exp.



Thy.



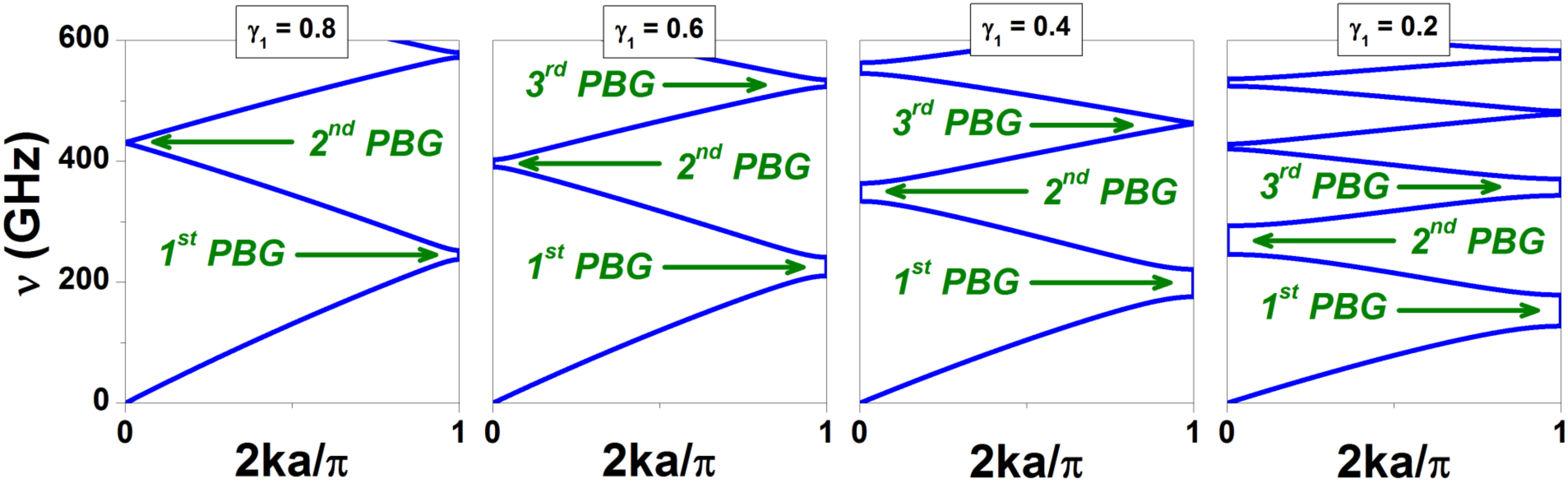
$$\gamma = \gamma_1 = \gamma_2$$



Two-period 1D plasmonic crystal embedded in 10 μm plasmonic cavity

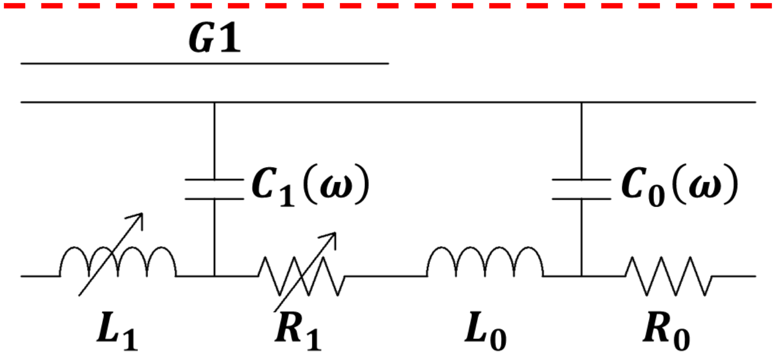
G. C. Dyer *et. al.*, *PRL* **109**, 126803 (2012)

Plasmonic Crystal Band Structure

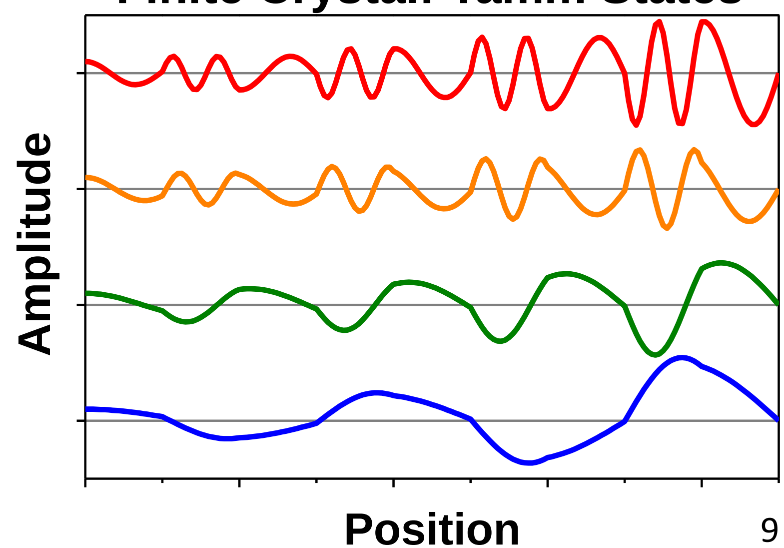


1D Kronig-Penney:

$$\cos 2ka =$$
$$\cos q_0 a \cos q_1 a - \frac{1}{2}\left(\frac{Z_0}{Z_1} + \frac{Z_1}{Z_0}\right) \sin q_0 a \sin q_1 a$$



Finite Crystal: Tamm States



G. R. Aizin and G. C. Dyer, *PRB* **86**, 235316 (2012)

Four Period Plasmonic Crystal

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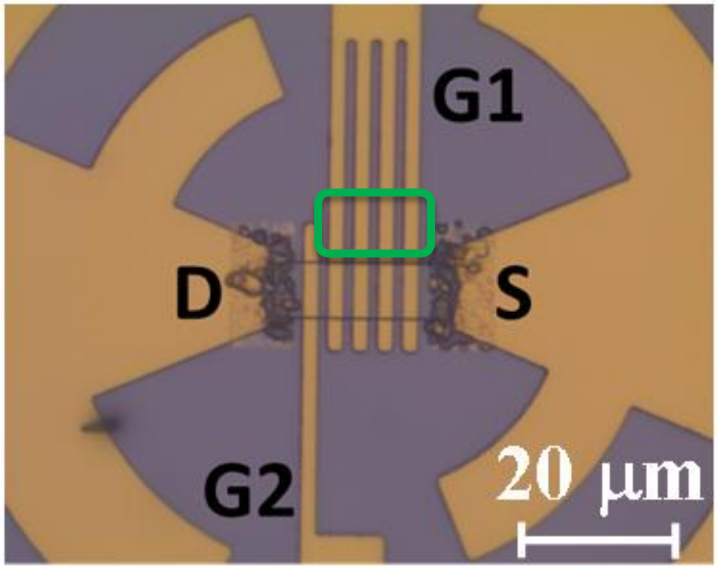
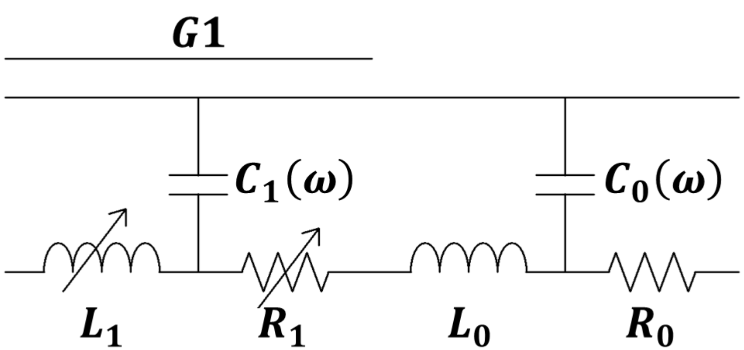
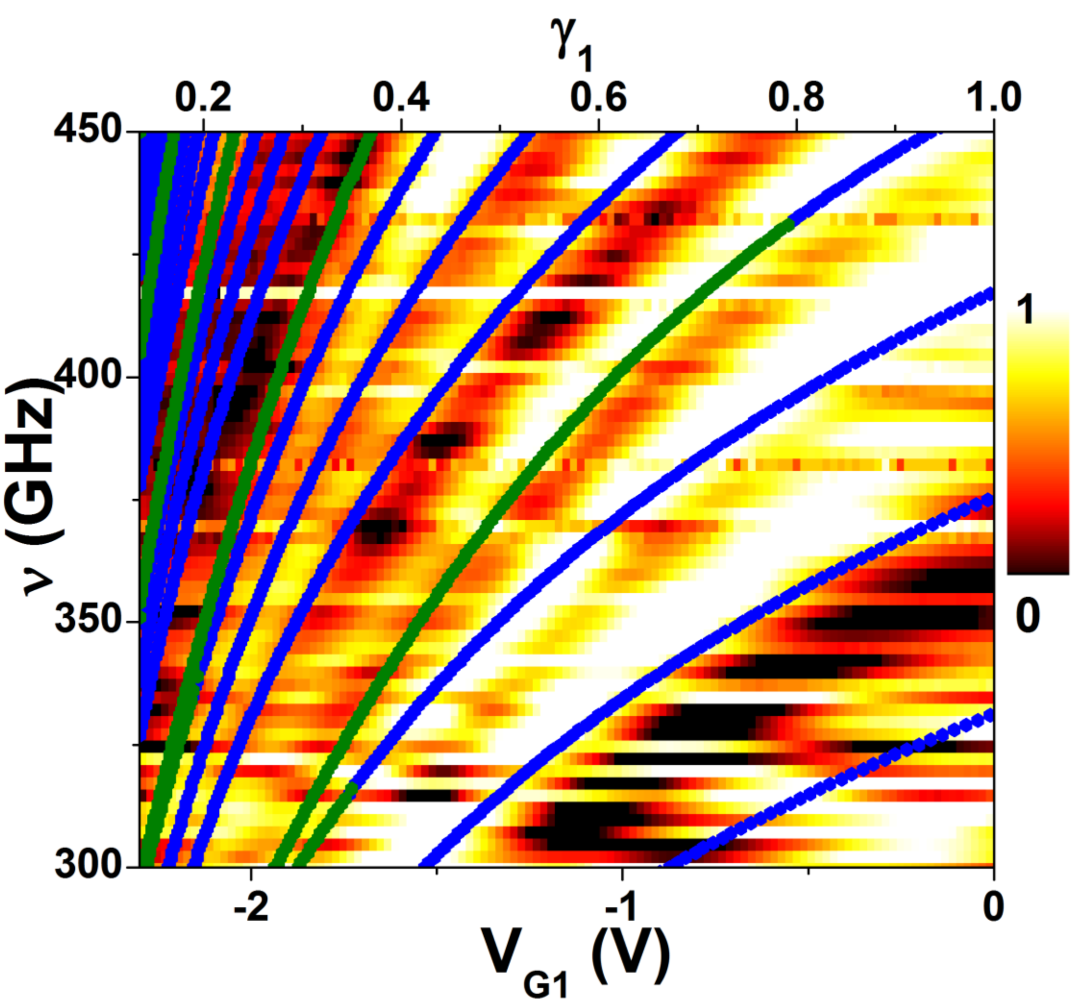


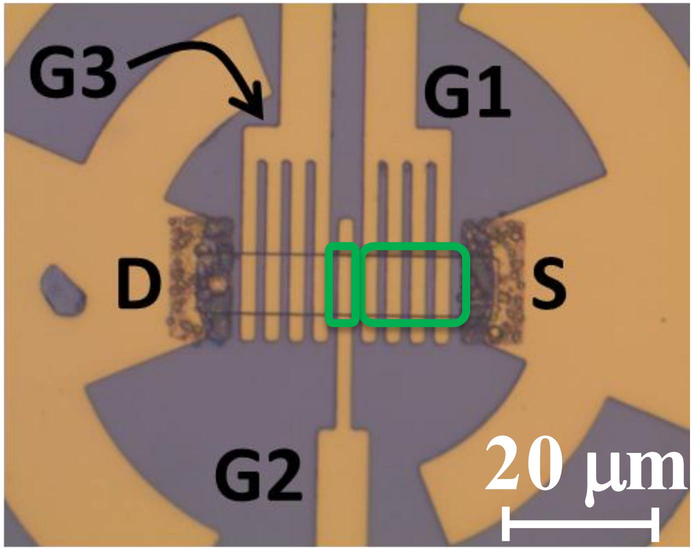


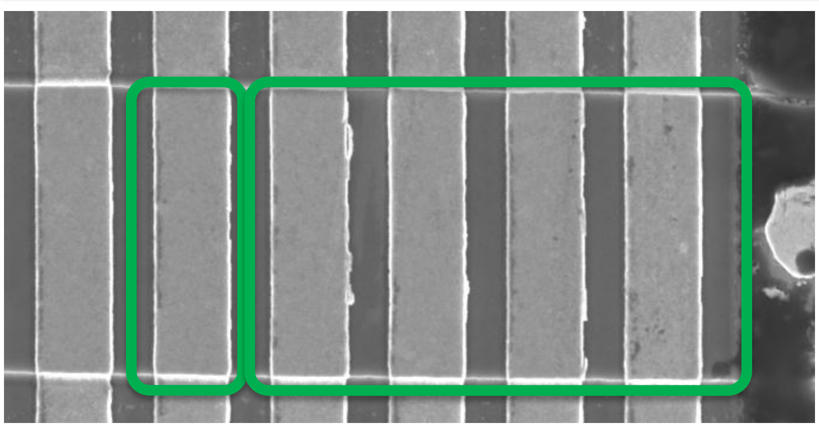


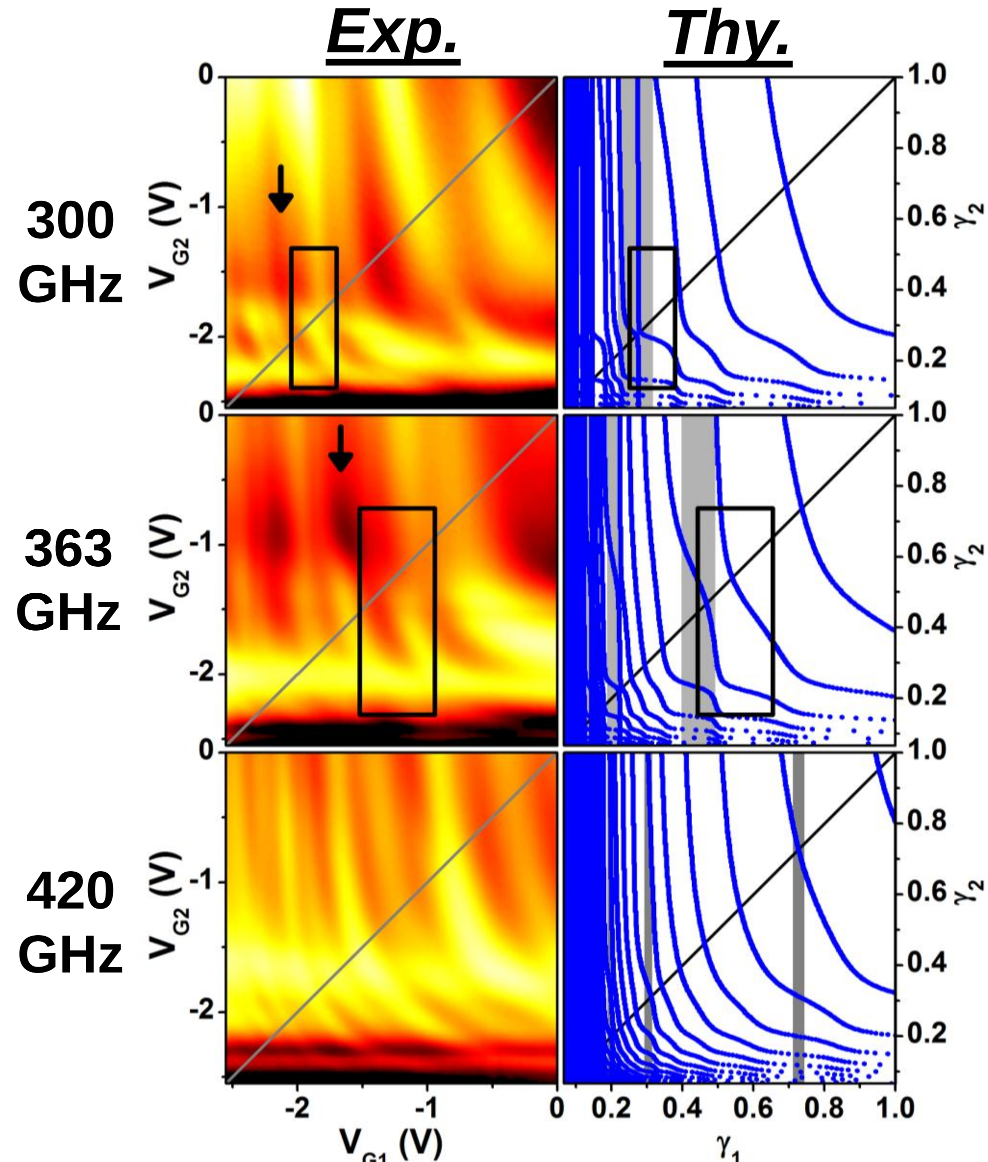
$$V_{G1} \to 0, L_1 \to \infty$$

G. R. Aizin and G. C. Dyer, *PRB* **86**, 235316 (2012) & G. C. Dyer *et. al.*, manuscript in preparation

Defect Probing of Tamm States

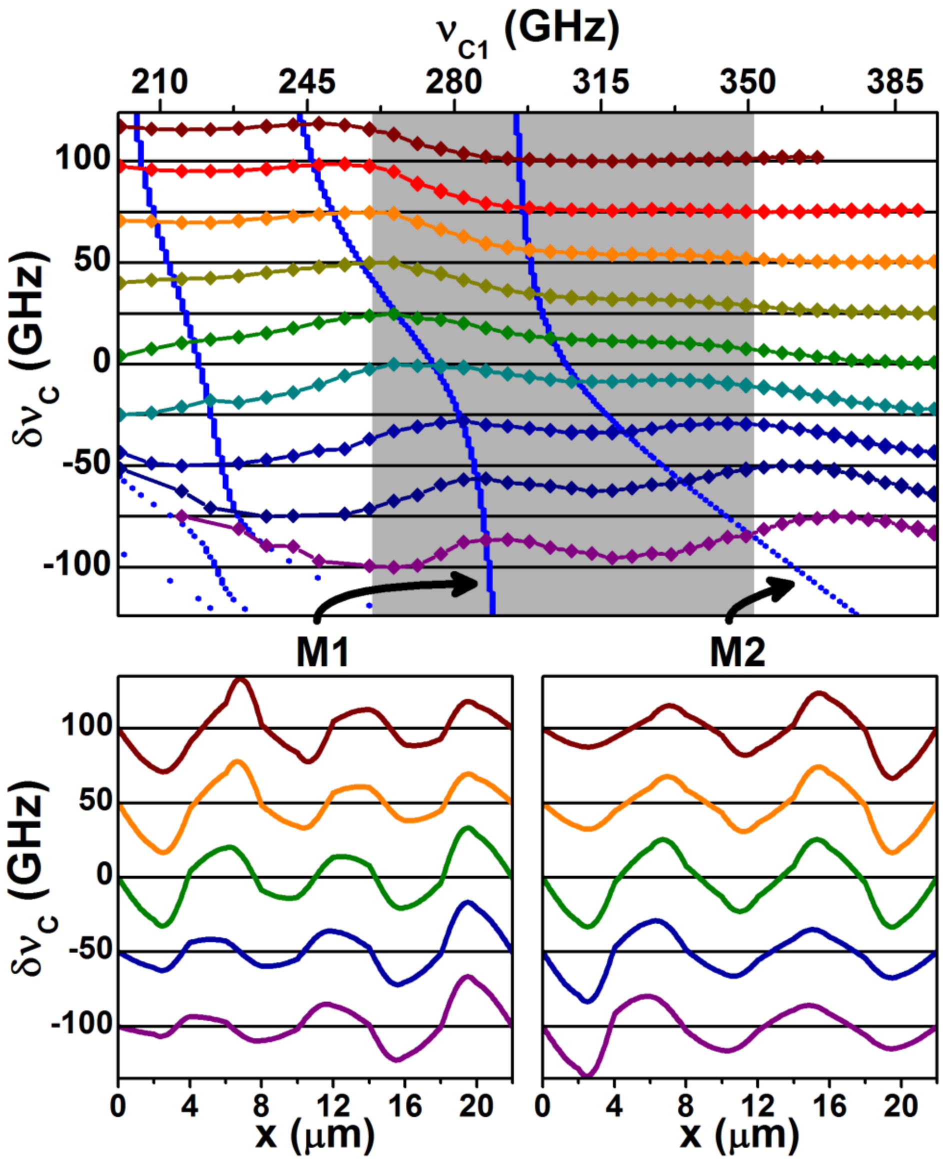






G. C. Dyer *et. al.*, manuscript in preparation

Active Control of Plasmonic EIT



210 GHz

$$\nu_{Cj} = \frac{\beta_C}{2\pi\sqrt{L_j C_j}}$$

$$\beta_C = \pi/a$$

$$\delta\nu_C = \nu_{C2} - \nu_{C1}$$

Calculated distributions of crystal-defect eigenmodes found in crystal in band gap

G. C. Dyer *et. al.*, manuscript in preparation

Credits & Acknowledgements

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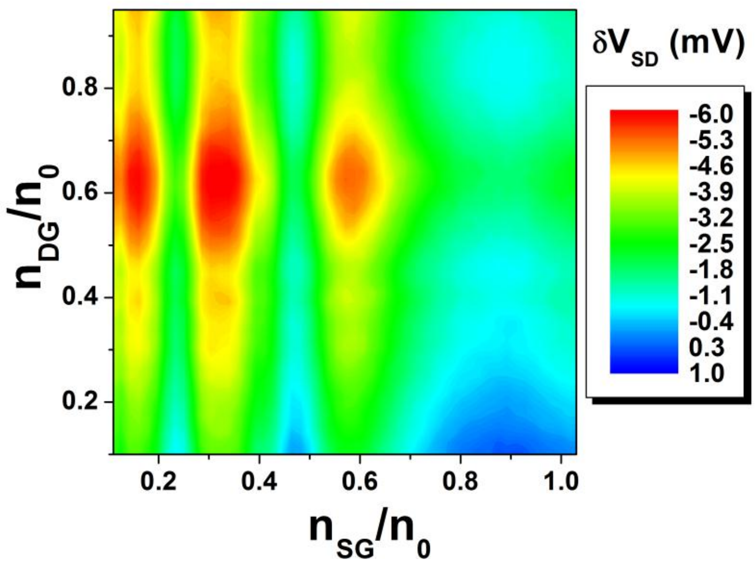
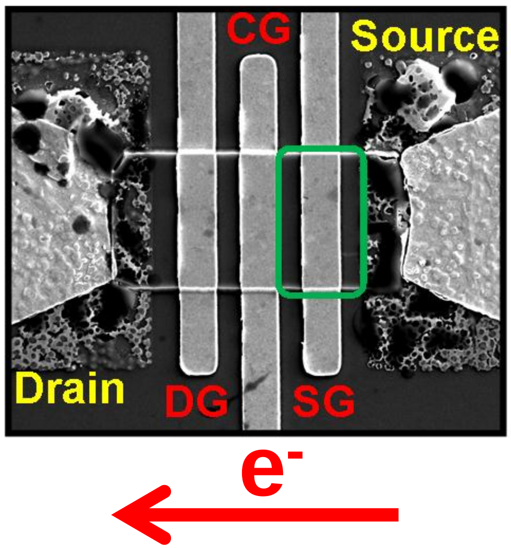
- **Grower:** John Reno
- **Device Design/Mask Layout**: Greg Dyer, Eric Shaner & S. James Allen
- **Processing**: Eric Shaner & Don Bethke
- **Characterization**: Greg Dyer & Albert Grine
- **Data Analysis**: Greg Dyer
- **Numerical Modeling**: Greg Dyer & Greg Aizin
- **Theory**: Greg Aizin & Greg Dyer

ADDITIONAL MATERIAL

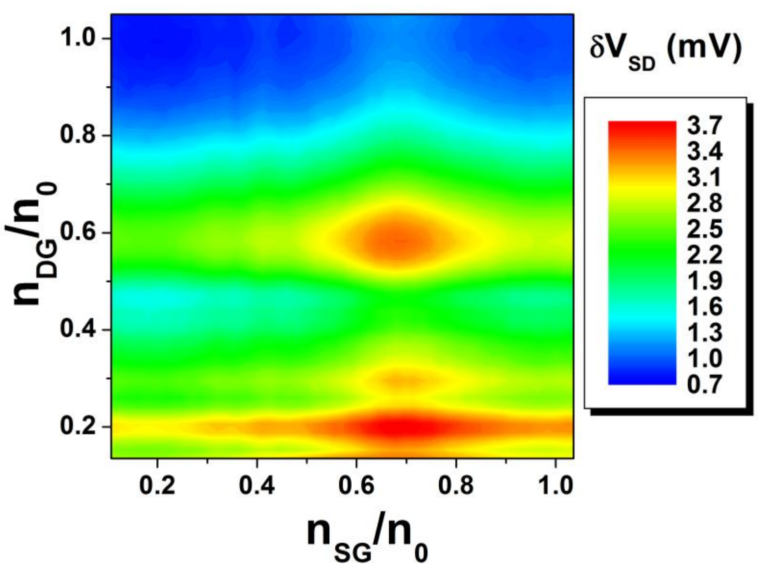
Source-Drain Bias Cavity Selection

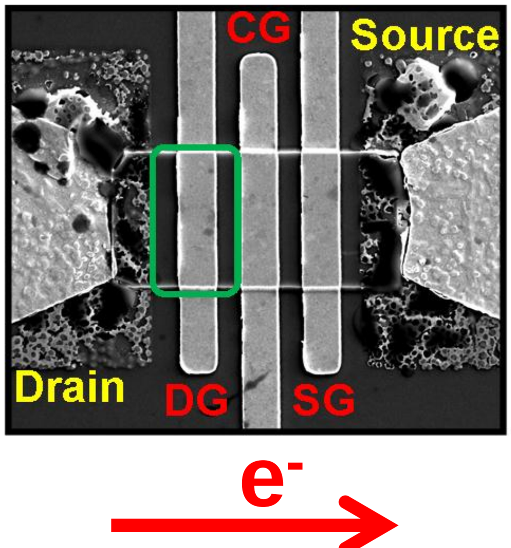




370 GHz

_I = +500 nA_



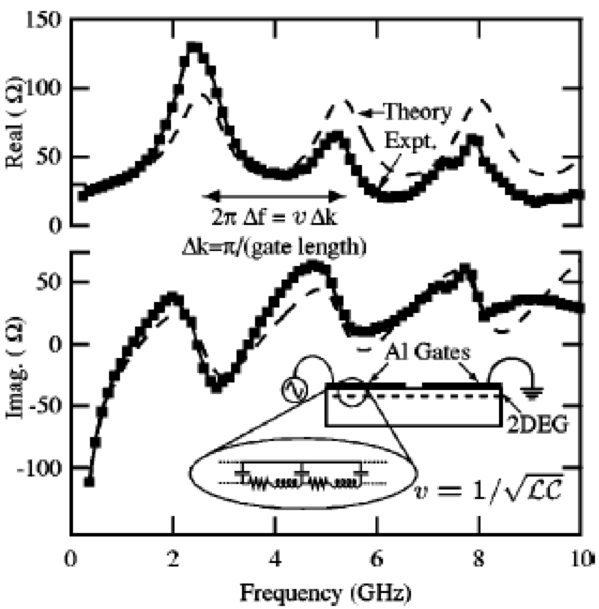


_I = -500 nA_

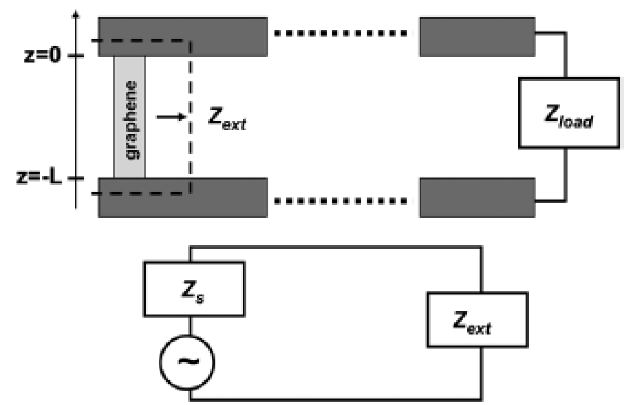
G. C. Dyer et. al., *APL* **100**, 083506 (2012)

Plasmonic TL Model

High frequency conductivity of the high-mobility two-dimensional electron gas



Graphene Terahertz Plasmon Oscillators



$$Z_0 = \sqrt{\frac{Z_{2DEG}}{i\omega C(\omega)}}$$

$$iq = \sqrt{i\omega C(\omega) Z_{2DEG}}$$

$$Z_{2DEG} = \frac{m^*}{e^2 n_{2D} \tau W}(1 + i\omega\tau)$$

$$\lim_{qd\to 0} C(\omega) = \frac{W\epsilon}{d}$$

(fully screened limit)

→ from Drude model

L is <u>kinetic inductance</u>

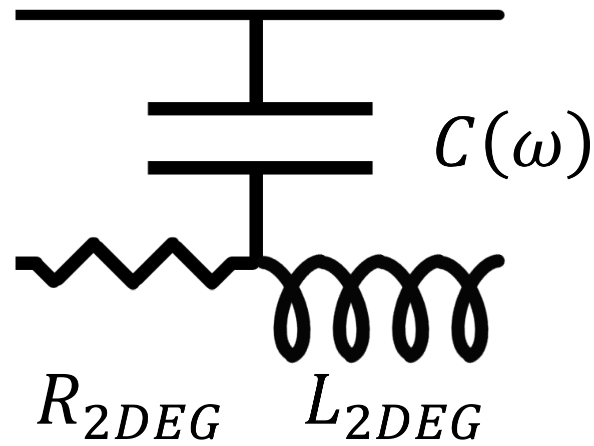
$$\lim_{qd\to\infty} C(\omega) = 2W\epsilon q$$

(unscreened limit)

P. J. Burke et. al., *APL* **76**, 745 (2000)   F. Rana, *IEEE Trans. on Nanotechnology* **7**, 91 (2008)

Generalized Plasmonic TL Model

$$C(\omega) = \frac{\Phi(x, z=0)}{\rho(x)} = W\epsilon q(1 + \coth[qd])$$



$$\tfrac{1}{2}\tilde{V}(x)\tilde{I}^*(x) = \tfrac{1}{2}\Phi(x,0)I^*(x)\ \xi^*(\omega, d)$$

where

$$\xi(\omega, d) = 1 - \frac{q\left(1 - e^{-2q'd}\cos[2q''d]\right)}{2q'(1 - e^{-2q^*d})} + \frac{q\, e^{-2q'd}\sin[2q''d]}{2q''(1 - e^{-2q^*d})}$$

$$\tilde{V}(x) \equiv \Phi(x, 0)$$
$$\tilde{I}(x) \equiv I(x)\xi(\omega, d)$$
$$\tilde{Z}_0 \equiv \frac{Z_0}{\xi(\omega, d)}$$

Homodyne Mixing in a HEMT

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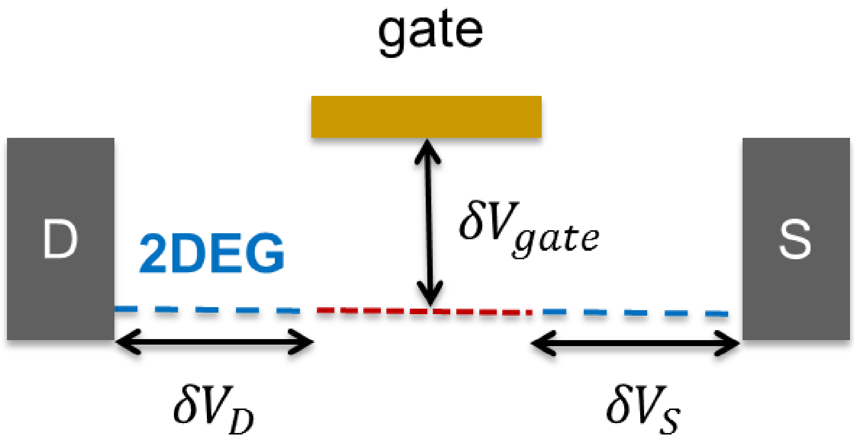
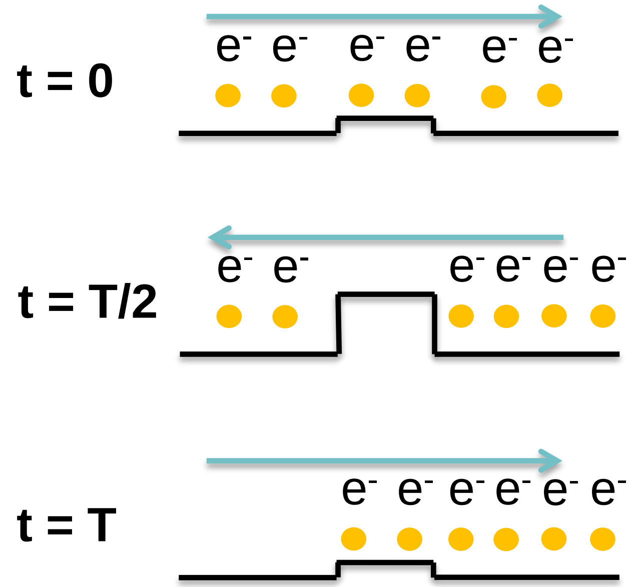




<u>THz field coupled to channel (blue) drives current across depleted region (red) which is rectified by gate THz field</u>

$$\langle \delta V_{SD} \rangle = \left\langle \left[\frac{\partial R_{chan}}{\partial V_{gate}} \delta V_{gate} e^{-i(\omega t + \emptyset)} \right] [\delta V_S - \delta V_D] e^{-i\omega t} G_{chan} \right\rangle$$

$$= \frac{1}{2} \left[\boxed{\boldsymbol{G_{chan} \frac{\partial R_{chan}}{\partial V_{gate}}}} \right] \delta V_{gate} [\delta V_S - \delta V_D] cos[\emptyset]$$

<u>∅ is relative phase between gate & channel THz potentials</u>

Hydrodynamic Model

$$\frac{\partial \delta v}{\partial t} + \delta v \frac{\partial \delta v}{\partial x} = \frac{e}{m}\frac{\partial \phi}{\partial x} \quad \& \quad \frac{\partial n}{\partial t} + \frac{\partial (n \delta v)}{\partial x} = 0$$

Self-consistent soln. of Euler's hydrodynamic eqn. of motion with continuity eqn.

- **Pros**:
  - little computational overhead
  - accurately predicts both linear and non-linear phenomena (absorption, mixing, emission)
- **Cons**:
  - non-trivial to phrase in Maxwell or circuit formalism
  - must choose boundary conditions
  - assumptions about screening
  - simple geometry

Detection, Mixing, and Frequency Multiplication of Terahertz Radiation by Two-Dimensional Electronic Fluid

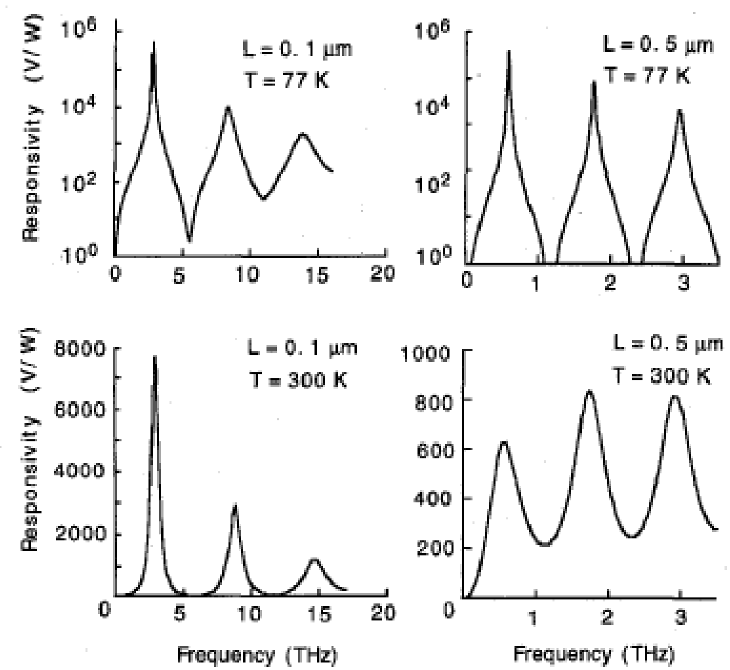
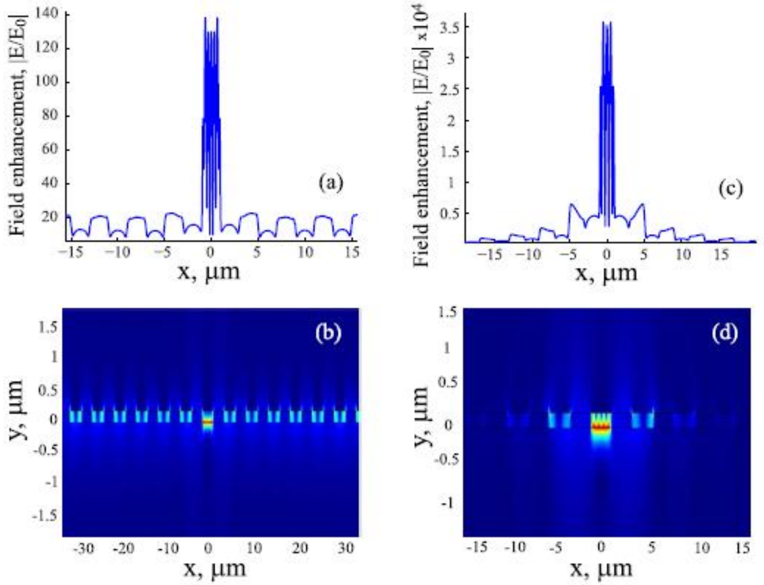


Fig. 5. Calculated responsivity as a function of frequency for 0.1 μm and 0.5 μm gate HEMT's at 77 K and 300 K. Parameters used in the calculation: $U_o = 0.5$ V, G = 1.5, $\nu = 15$ cm ^{2}s, m = $0.063 m_o$, $\mu = 300{,}000$ cm^2/Vs at 77 K, $\mu = 8{,}000$ cm^2/Vs at 300 K.

M. I. Dyakonov and M. S. Shur, *PRL* **71**, 2465 (1993) & *IEEE Trans. on Electron Devices* **43**, 380 (1996)

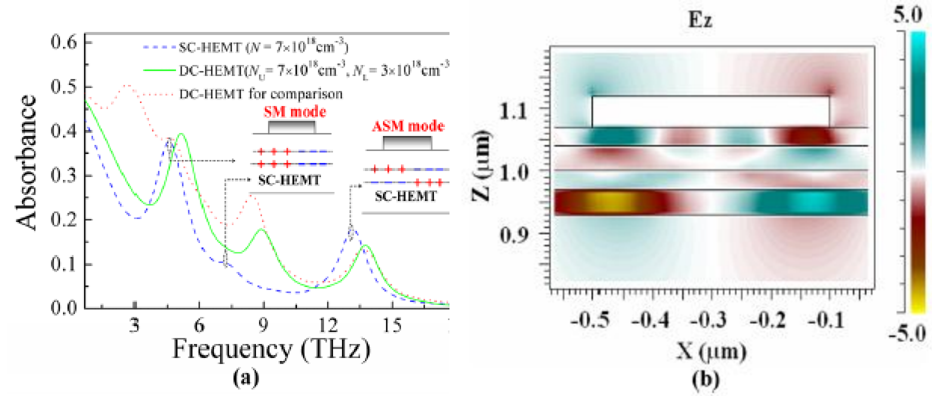
FDTD (Full EM)

Tailoring Terahertz Near-Field Enhancement via Two-Dimensional Plasmons



A. R. Davoyan et. al., *PRL* **108**, 127401 (2012)

The plasmonic resonant absorption in GaN double-channel high electron mobility transistors



L. Wang et. al., *APL* **99**, 063502 (2011)

- **Pros**:
  - direct solution of EM parameters (fields, absorption, transmission, etc.)
  - can embed 2DEG in complex geometry including material parameters
  - Maxwell imposes boundary conditions
- **Cons**:
  - large computational overhead
  - expensive
  - “intuition before computation”

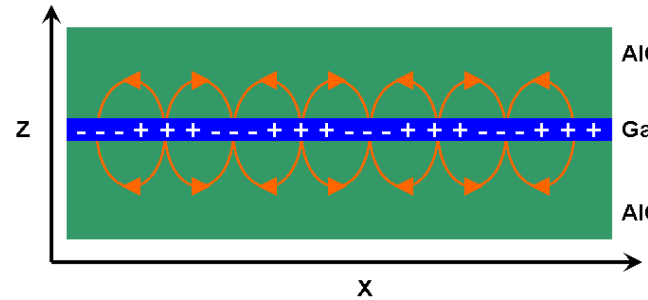
Generalized Plasmonic TL Model

The 2D plasmon is in general a TM wave:

P = ½ VI* is correct only for TEM wave in fully screened limit

$$P(x) = \frac{1}{2}\iint S_x dydz = -\frac{W}{2}\iint E_z H_y dydz$$

$$= \frac{1}{2}\Phi(x,0)\mathrm{I}^*(x)\,\xi^*(\omega,d)$$



$$\xi(\omega,d) = 1 - \frac{q\left(1 - e^{-2q'd}\cos[2q''d]\right)}{2q'\left(1 - e^{-2q^*d}\right)} + \frac{q\,e^{-2q'd}\sin[2q''d]}{2q''\left(1 - e^{-2q^*d}\right)}$$

$$P(x) \to \begin{cases} \lim\limits_{qd\to 0} P(x) = \frac{1}{2}\Phi(x,0)\mathrm{I}^*(x) \\ \lim\limits_{\tau,qd\to\infty} P(x) = \frac{1}{4}\Phi(x,0)\mathrm{I}^*(x) \end{cases}$$

fully screened limit

unscreened limit

Effective V, I & Z

$$\tfrac{1}{2}\tilde{V}(x)\tilde{I}^*(x) = \tfrac{1}{2}\Phi(x,0)I^*(x)\,\xi^*(\omega,d)$$

$$\boxed{\begin{aligned}\tilde{V}(x) &\equiv \Phi(x,0)\\ \tilde{I}(x) &\equiv I(x)\xi(\omega,d)\\ \tilde{Z}_0 &\equiv \frac{Z_0}{\xi(\omega,d)}\end{aligned}}$$

Characteristic Impedance of Microstrip Lines

JOHN R. BREWS, MEMBER, IEEE

FOR non-TEM structures such as microstrip lines it generally is agreed that the characteristic impedance is not unique. It also is agreed that the root of this uncertainty is the longitudinal field components of non-TEM modes. Because of these components, current and voltage are not uniquely defined in terms of the usual TEM path integrals of the fields. Faced with an ambiguity in the meaning of current I and voltage V a variety of results for the characteristic impedance Z_0 is obtained.

J. R. Brews, *IEEE Trans. on Microwave Theory and Techniques* **35**, 30 (1987)

Above definitions are not unique, but accurately address physics:

1. *Effective potential $\tilde{V}(x)$ is continuous*
2. *Power $\tilde{V}(x)\tilde{I}^*(x)$ is continuous*
3. *Discontinuity in <u>real</u> carrier density $\rho(x)$ and <u>real</u> current $I(x)$ is consistent with edge charge accumulation at step-like boundary*

Inductance Comparison

Treat gated 2DEG like a single wire loop

Magnetic flux per unit length through x-z plane

$$\Phi_m \sim \frac{\mu_0 I d}{W} = I L_{geometric}$$

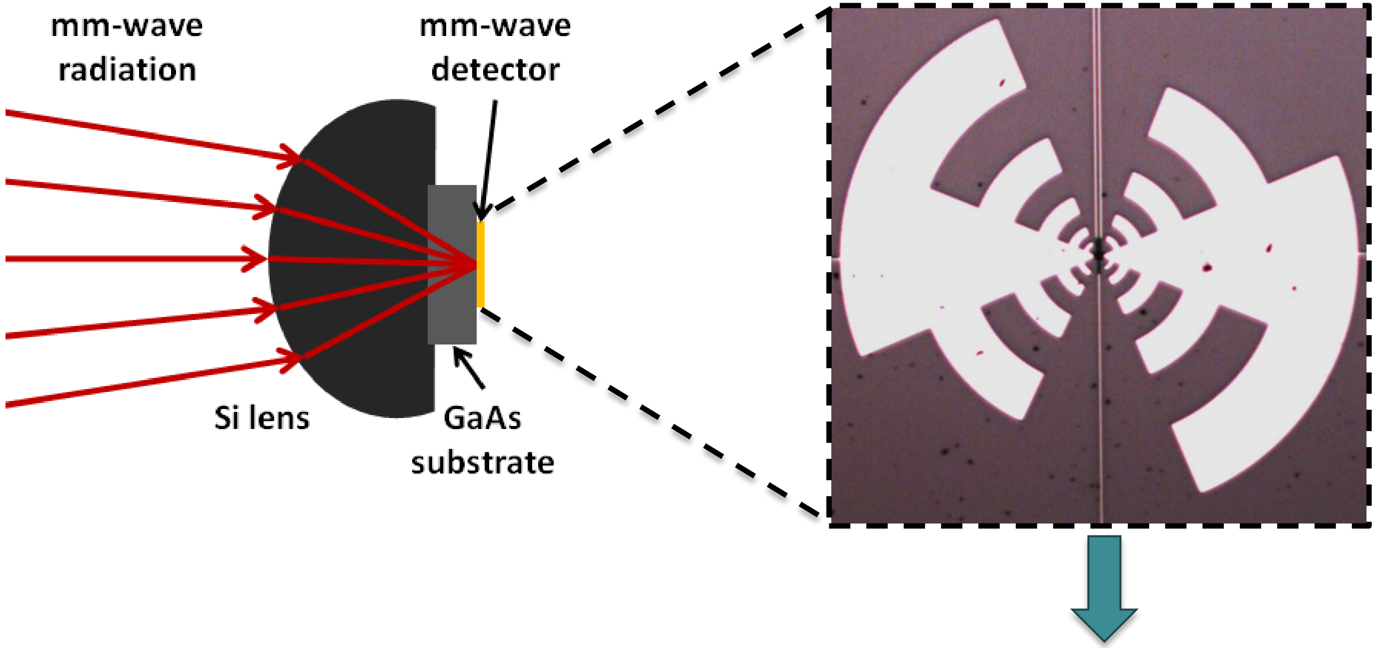
Inductance per unit length along x-direction

$$L_{kinetic} = \frac{m^*}{e^2 n_{2D} W} \sim 50\ \mu_0$$

$$L_{geometric} = \frac{d}{W}\mu_0 \sim 0.05\ \mu_0$$

Antenna Coupled THz Detector

Sandia National Laboratories



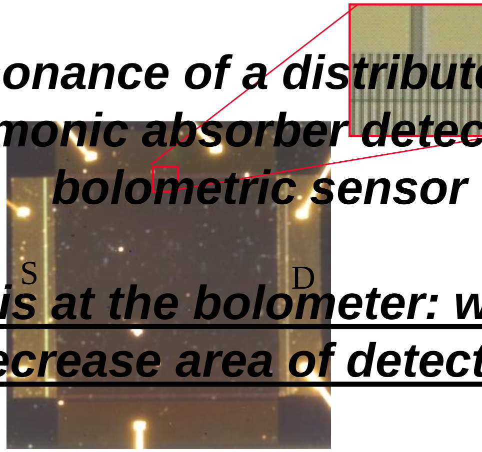
Five terminal HEMT at antenna vertex:
S, D and gates (SG, CG and DG)

Self complementary antenna:
impedance of ~72 Ω on substrate

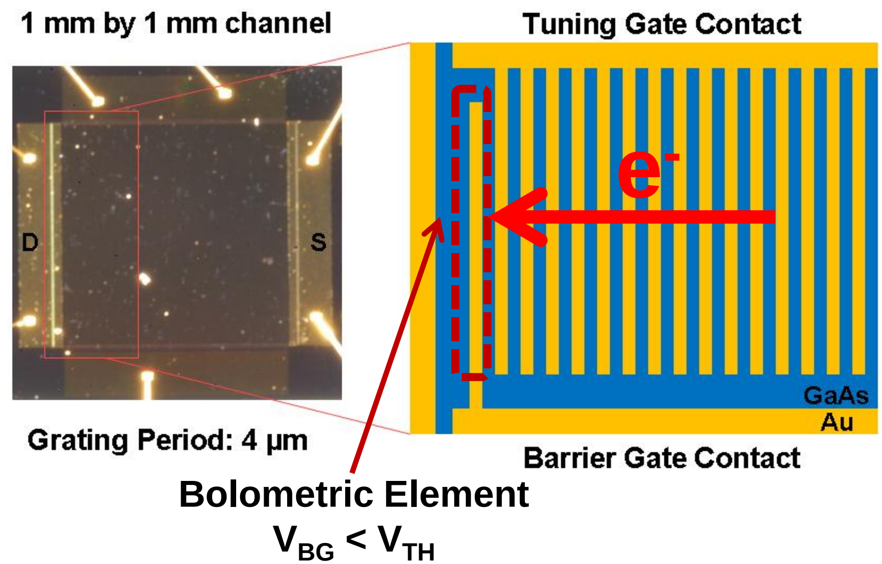
G. C. Dyer et. al., *APL* **97**, 193507 (2010) & *APL* **100**, 083506 (2012)

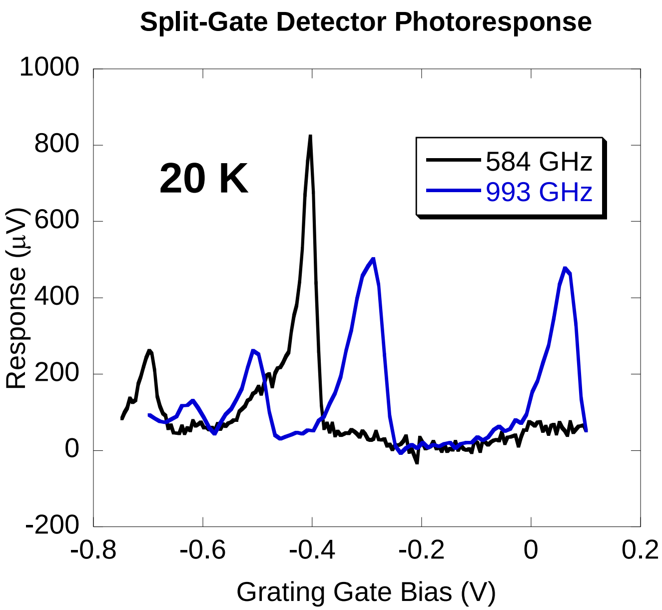
Resonant Terahertz Response

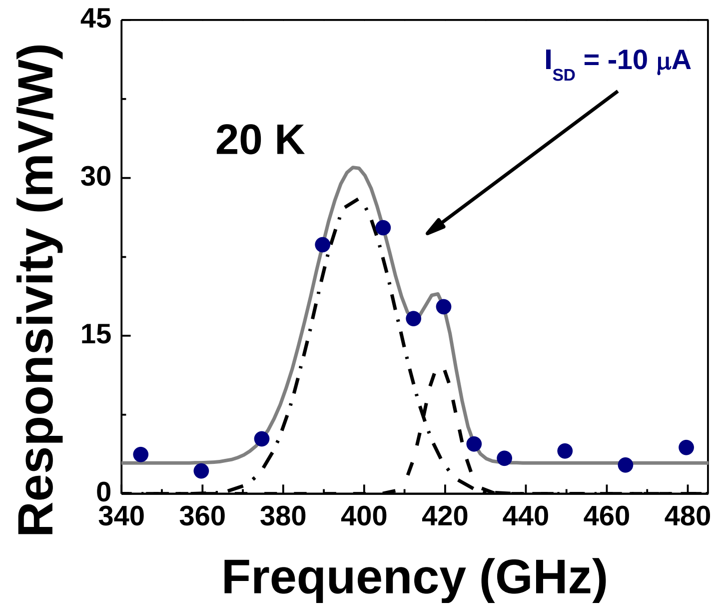
Resonance of a distributed 2D plasmonic absorber detected by bolometric sensor



<u>Action is at the bolometer: what if we decrease area of detector?</u>







Growth Sheet

EPI-A GROWTH SHEET EA0741

SAMPLE ID: EA0741
DATE: 02-May-01
GROWER: Reno, J.
OBJECTIVE: High Mobility Structure
CUSTOMER: Lilly,M
MATERIAL: GaAs, AlGaAs

Structure

#	Material	Thickness	Dopant	Density	Temp.	SL	Comment
1	GaAs	10.0 nm	undoped		635 °C		Cap
2	AlGaAs	98.0 nm	undoped		635 °C		24.1%
3	delta-dope	0.0 nm	Si (n)	1.00E+12	635 °C		
4	AlGaAs	75.0 nm	undoped		635 °C		Upper Setback 24.1%
5	GaAs	30.0 nm	undoped		635 °C		QW
6	AlGaAs	95.0 nm	undoped		635 °C		Lower Setback24.1%
7	delta-dope	0.0 nm	Si (n)	1.00E+12	635 °C		
8	AlGaAs	98.0 nm	undoped		635 °C		24.1%
9	GaAs	3.0 nm	undoped		635 °C	[x300	Smoothing & EtchStop SL
10	AlGaAs	10.0 nm	undoped		635 °C	]	54.8%
11	GaAs	100.0 nm	undoped		635 °C		Buffer

Substrate Information

Ingot: G079K3400
Slice:
Material: GaAs
Orientation: (100)
Thickness: 625 µm
Diameter: 3"
Type: undoped
Vendor: AXT

Source Information

Source	Temp °C	Flux	G.R. ML/s	Rheed	UFG	Comment
Al7	1155.0		0.242	Yes	Yes	
As2_Va	175.0		1.760	Yes	Yes	
As2C	650.0		0.000	No	Yes	
As2X	390.0		0.000	No	Yes	
Ga3	1158.0		0.762	Yes	Yes	GaAs, 24.1% AlGaAs
Ga9	1090.0		0.199	Yes	Yes	54.8% AlGaAs
Rotate	-15.0		0.000	No	Yes	
Rotate	-5.0		0.000	No	Yes	Buffer
Si	1212.0		0.000	No	Yes	

Notes and Comments:

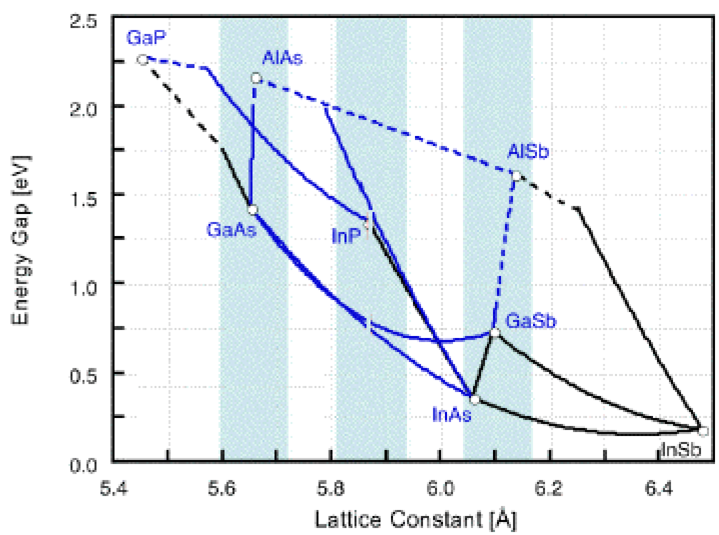
Duplicate of EA0739 but grown with lower As flux.

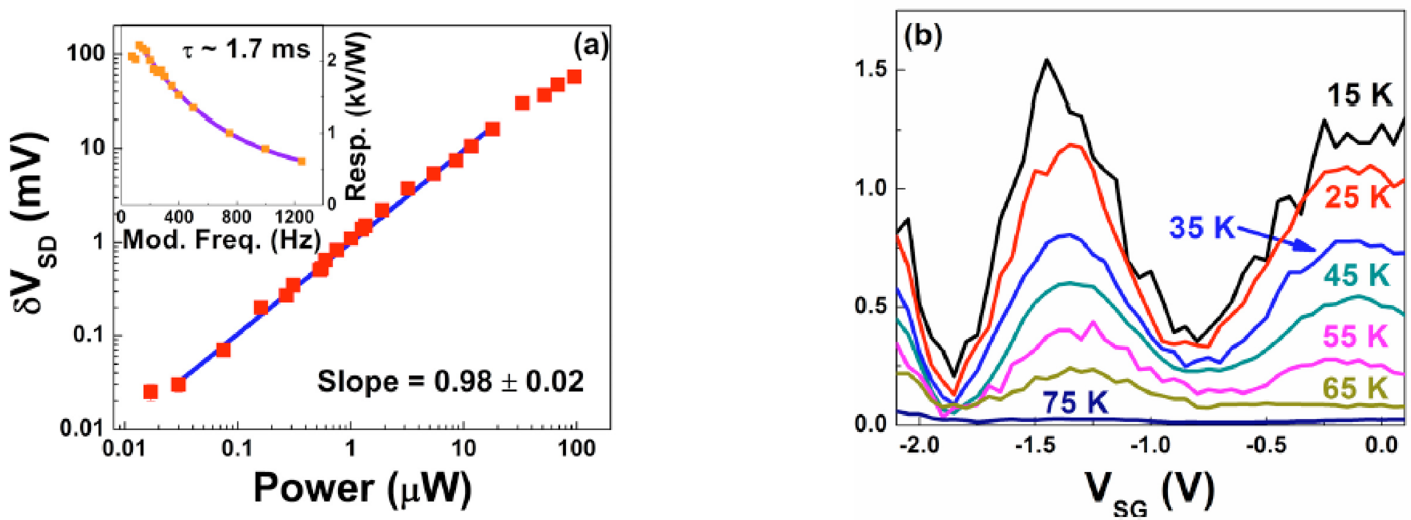
Characterization Results:

1

GaAs / $Al_xGa_{1-x}As$

x = .24




(a)
τ ~ 1.7 ms
Resp. (kV/W)
Mod. Freq. (Hz)
0
400
800
1200
0
1
2
δV_SD (mV)
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Power (μW)
Slope = 0.98 ± 0.02
(b)
1.5
1.0
0.5
0.0
-2.0
-1.5
-1.0
-0.5
0.0
V_SG (V)
15 K
25 K
35 K
45 K
55 K
65 K
75 K