Electrodynamics of Plasma Oscillations in Semiconductor Microdevices with Two-Dimensional Electron Channels

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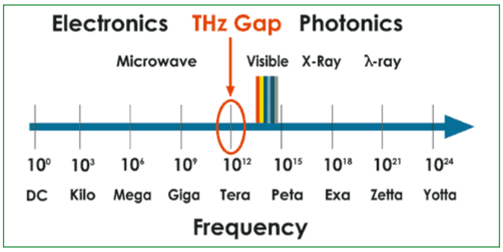
Outline of the Talk

1. Can plasmonic devices fill a THz gap?
2. Remarks on the fundamentals of two-dimensional plasmons. Plasmon modes in a HEMT structure. When the electromagnetic effects are important?
3. Slot diode with two-dimensional electron channel (unscreened plasmons): electromagnetic description
4. Screened plasma oscillations (electromagnetic description). Interaction of gated (screened) and ungated (unscreened) plasmons in a HEMT structure
5. Conclusions

Applications of THz Technology



- Imaging:
  - THz tomography
  - Explosive and mine detection
  - Security scanners
- Biotechnology: molecular sensors
- Radio astronomy
- Atmospheric measurements
- Fusion Plasma diagnostics
- IC interconnects
- Advanced short-range radars
- Short Range Hidden Communications
- "Last mile internet" solutions

Terahertz Gap

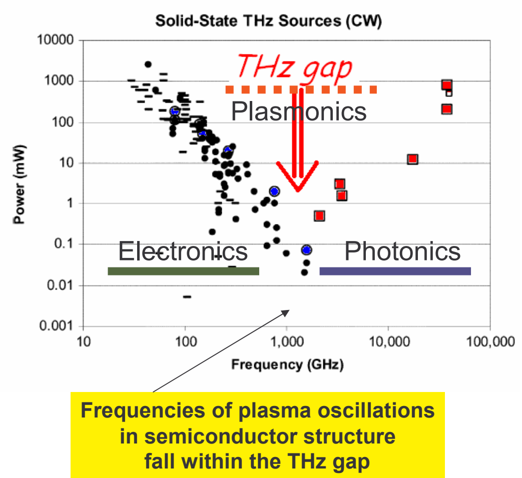
■ Quantum cascade lasers

● Frequency multipliers

\- Other solid-state electronic sources

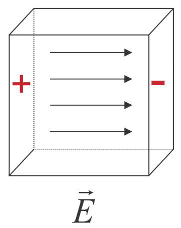
Blue symbols correspond to cryogenic sources

From: T. W. Crowe *et al*, IEEE J. Solid-State Circuits **40**, 2104 (2005)

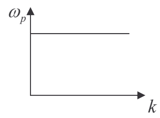


Dispersion of Plasma Waves: 2D vs 3D

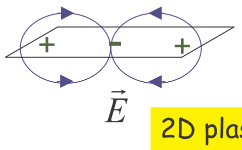
3D



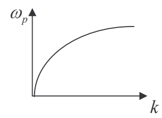
$$\omega_p = \sqrt{\frac{e^2 N_{3D}}{\varepsilon \varepsilon_0 m}}$$



2D

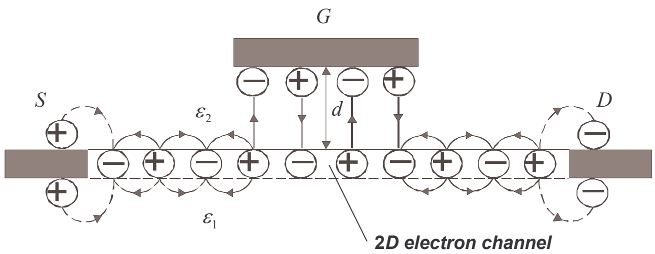


$$\omega_p = \sqrt{\frac{e^2 N_{2D}}{2 \varepsilon \varepsilon_0 m} k}$$



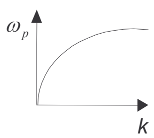
2D plasmons: (i) stronger couple to EM radiation
(ii) are tunable
(iii) transfer EM energy

Plasmon Modes in a HEMT Structure



Ungated 2D plasmons

$$\omega_p = \sqrt{\frac{e^2 N_{2D}}{m^* \varepsilon_0 (\varepsilon_1 + \varepsilon_2)} k}$$



R.H. Ritchie, PR (1957)
F. Stern, PRL (1967)

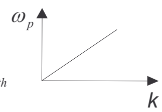
Gated 2D plasmons (*kd* << 1)

$$\omega_p = k \sqrt{\frac{e^2 N_{2D} d}{m^* \varepsilon_0 \varepsilon_2}}$$

A.V. Chaplik, JETP (1972)

Gradual channel approximation:

$$N_{2D} = \frac{\varepsilon_0 \varepsilon}{ed} U_0 \, , \quad \text{where } U_0 = U_g - U_{th}$$

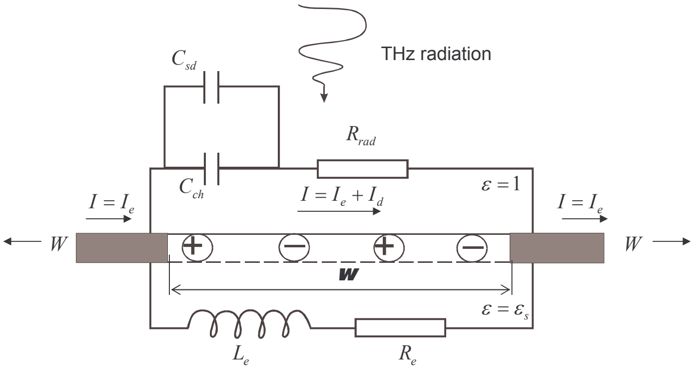


$$\omega_p = sk \, , \quad \text{where } s = \sqrt{\frac{eU_0}{m^*}}$$

***S>>V$_{drift}$* (!!!)**

M. Dyakonov, M.Shur
PRL (1993)

Slot Diode with 2DElectron Channel



$$C_{ch} = \frac{\varepsilon_0 \varepsilon}{k} \cdot \frac{L}{w}$$

$$L_e = \frac{m^*}{e^2 N} \cdot \frac{w}{L}$$

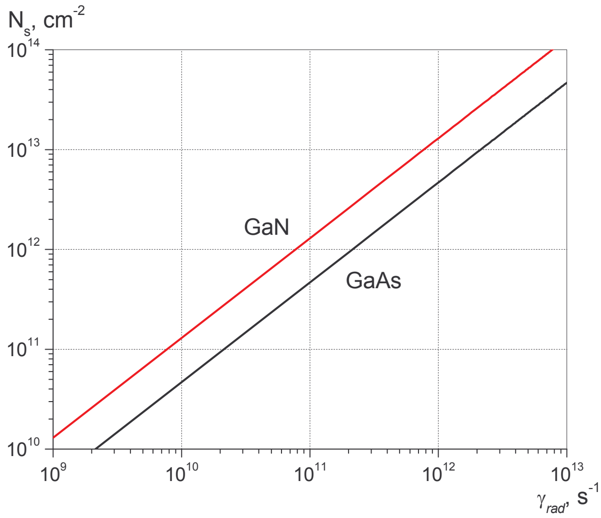
$$R_e = \frac{m^* \nu}{e^2 N} \cdot \frac{w}{L}$$

Electrostatic description:

$R_{rad} = 0$ **&** $C_{sd} = 2.83 \times 10^{-3} (\varepsilon_s + 1) \ln\left[4\left(1 + 2\frac{W}{w}\right)\right] L[\mathrm{fF}] \quad \left(\frac{W}{w} > 0.75\right)$

M.S. Shur, GaAs Devices and Circuits, Plenum, N.Y., 1987
P.J. Burke et al, *Appl. Phys. Lett.*, vol. 76, No. 6, pp. 745, 2000
V. Ryzhii et al, *Appl. Phys.*, vol. 93, No. 12, pp.10041, 2003

Radiative Damping of Uniform Oscillating Current in a Homogeneous 2D Electron System



$$\gamma_{rad} = \frac{e^2 N_s}{2m^*} \frac{Z_0}{\sqrt{\varepsilon}}$$

V.V. Popov et al. JETP (1996)

S.A. Mikhailov Phys. Rev. B (1998)

Electromagnetic Description of Plasmons in FET Structures

- The Maxwell equations are re-written in the Fourier representation
- Using the electrodynamic boundary conditions in the channel and gate planes, the Fourier amplitudes of the oscillating-electron-current density are related to those of the in-plane THz electric field in the gate and electron channel planes
- Equalizing the sheet electron current density obtained in the previous steps to that in the Ohm's law yields the integral equation for the current density in the gate contact
- The integral equation is solved numerically by the Galerkin method through its projection on an orthogonal set of the Legendre polynomials

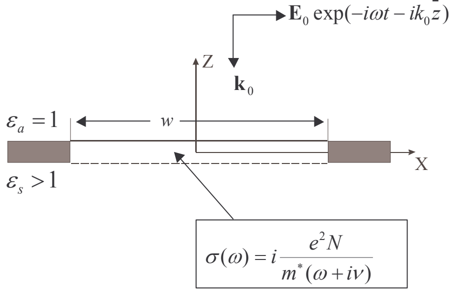
Sheet conductivity of the 2D electron channel

$$\sigma(\omega) = i\frac{e^2 N_{2D}}{m^*(1 - i\omega\tau)}$$

V.V. Popov et al., JETP (1996, 1998, 2002) V.V. Popov et al. JAP (2003, 2005)

Electromagnetic Description of a Slot Diode with 2D Electron Channel

V.V. Popov et al., Semiconductors (2005)



Integral equation for the electric field in the slot:

$$\sigma(\omega)E_x(x) = \int_{-w/2}^{w/2} G(x,x')E_x(x')dx' + \frac{2E_0}{Z_0}$$

$$G(x,x') = \int_{-\infty}^{\infty} dk_x G(k_x)\exp\left[ik_x(x - x')\right]$$

$$G(k_x) = \frac{(\chi_a + \chi_s)}{Z_0} \qquad \chi_{a(s)} = \varepsilon_{a(s)}\frac{k_0}{k_z}$$

$$k_z = \pm\sqrt{k_0^2\varepsilon_{a(s)} - k_x^2} \qquad k_0 = \frac{\omega}{c}$$

$$E_x(x) = \sum_{n=0}^{\infty} a_n P_n(2x/w)$$

Induced field in the ambient medium:

$$\mathbf{E}_a^{(ind)}(\mathbf{r}) = \mathbf{E}_0\exp(ik_0 z) + \int_{-\infty}^{\infty}\mathbf{E}_a^{(sc)}(k_x)\exp(i\mathbf{k}_a\mathbf{r})dk_x$$

Total field in the substrate:

$$\mathbf{E}_a^{(tot)}(\mathbf{r}) = \int_{-\infty}^{\infty}\mathbf{E}_s^{(sc)}(k_x)\exp(i\mathbf{k}_s\mathbf{r})dk_x$$

Characteristic Electromagnetic Lengths

V.V. Popov et al., Semiconductors (2005)

Scattering Length:

$$L_{a(s)}^{(sc)} = \frac{P_{a(s)}}{P_0}, \quad L^{(sc)} = L_a^{(sc)} + L_s^{(sc)}$$

$$P_{a(s)} = \frac{\pi}{Z_0} \int_{-k_0\sqrt{\varepsilon_{a(s)}}}^{k_0\sqrt{\varepsilon_{a(s)}}} \mathbf{n}_{a(s)} \frac{\mathbf{k}_{a(s)}}{k_0} \left|\mathbf{E}_{a(s)}^{(sc)}(k_x)\right|^2 dk_x$$

Absorption Length:

$$L^{(ab)} = \frac{Q}{P_0},$$

$$Q = \frac{1}{2} \int_{-w/2}^{w/2} \left|E_x(x,0)\right|^2 \mathrm{Re}\left[\sigma(\omega)\right] dx$$

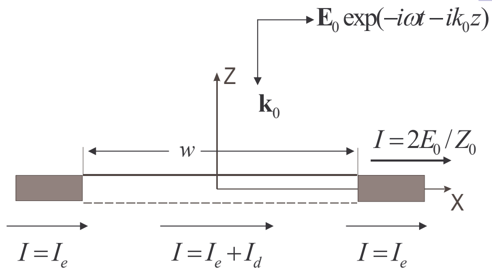
Extinction Length:

$$L^{(ex)} = \frac{4\pi}{\left|E_0\right|^2} \mathrm{Re}\left[\mathbf{E}_0^* \mathbf{E}_a^{(sc)}(k_x = 0)\right]$$ – **optical theorem**

$$W = P_a + P_s + Q \quad \Rightarrow \quad L^{(ex)} = L^{(sc)} + L^{(ab)}$$ – **energy conservatio**

High-Frequency Impedance of the Slot Diode

V.V. Popov et al., Semiconductors (2005)



$$Z = R + iX = -\frac{1}{I} \int_{-w/2}^{w/2} E_x(x) dx$$

$$I = \frac{2E_0}{Z_0}$$

Characteristic resistances of the diode:

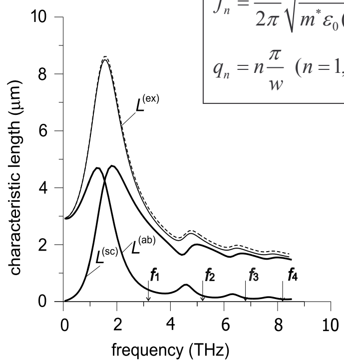
$$R = R_e + R_{rad} = \frac{Z_0 L^{(ex)}}{4} \qquad R_e = \frac{Z_0 L^{(ab)}}{4} \qquad R_{rad} = \frac{Z_0 L^{(sc)}}{4}$$

Terahertz Response of the Slot Micro-Diode

Characteristic Lengths:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{e^2 N q_n}{m^* \varepsilon_0 (1+\varepsilon_s)}}$$

$$q_n = n\frac{\pi}{w} \quad (n = 1, 2, 3, \ldots)$$



$w = 1.3$ μm

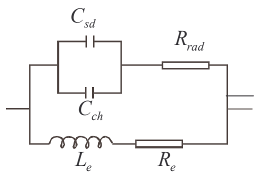
$N = 3 \cdot 10^{12}$ cm^{-2}

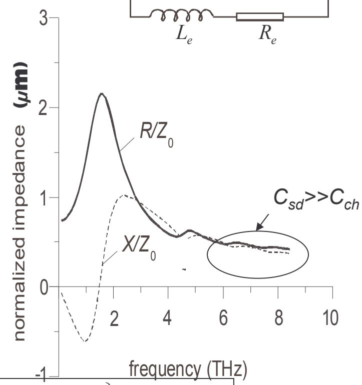
$\nu = 4.35 \cdot 10^{12}$ s^{-1}

$\varepsilon_s = 13.88$

$m^* = 0.042 m_0$

Diode Impedance:

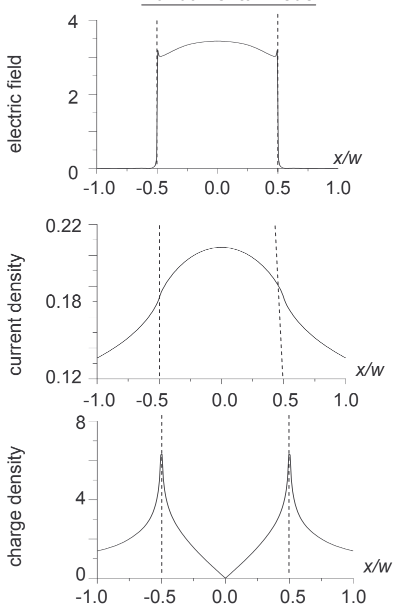


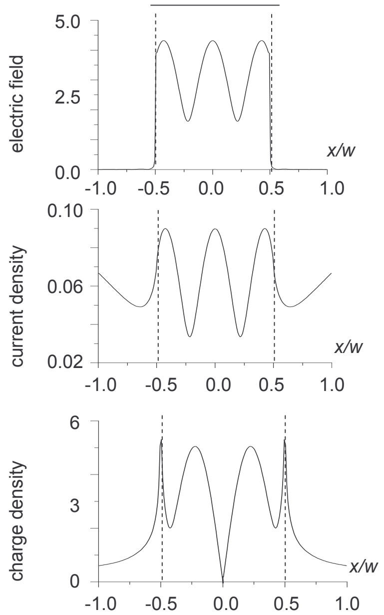


Electrostatic description: $\left.\begin{matrix} R \to 0 \\ X \to 0 \end{matrix}\right\}$ at $f \to \infty$

V. Ryzhii et al, *Appl. Phys.*, vol. 93, No. 12, pp.10041, 2003

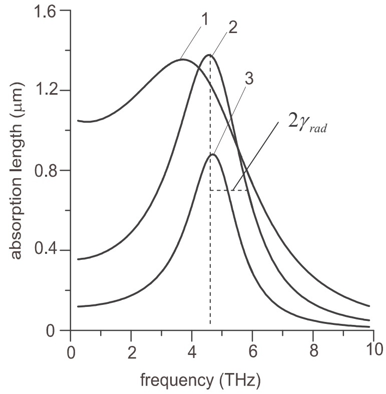
Plasmon Modes of the Slot Diode

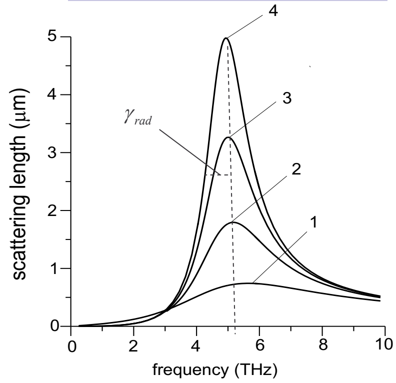




Terahertz Response of the Slot Nano-Diode

В.В. Попов и др., ФТП (2005)





$w = 0.1\,\mu\mathrm{m}$

$N = 3\cdot10^{12}\,\mathrm{cm}^{-2}$

$\varepsilon_s = 13.88$

$m^* = 0.042 m_0$

1 – $\nu = 2\cdot10^{13}$ s-1

2 – $\nu = 7\cdot10^{12}$ s-1

3 – $\nu = 2.3\cdot10^{12}$ s-1

4 – $\nu = 0$

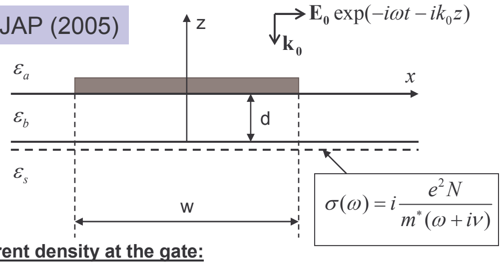
$A = A_{\max}$

@ $\gamma_{rad} = \nu$

$Z_{\mathrm{diode}} = Z_0$

Electromagnetic Modelling of Gated Plasma Oscillations in 2D Electron Channel

V.V. Popov et al., JAP (2005)



Integral equation for current density at the gate:

$$\int_{-l/2}^{l/2} \hat{G}(x,x') I_x(x',d)\, dx' = 2\sqrt{\varepsilon_a}\frac{\hat{G}_0}{Z_0}\mathbf{E}_0, \quad \hat{G}(x,x') = \int_{-\infty}^{+\infty} \hat{G}(k_x)\exp\left[ik_x(x-x')\right]dk_x, \quad \hat{G}_0 = \hat{G}(k_x = 0)$$

$$\hat{G}(k_x) = \frac{\mathrm{ctg}(k_{z,b}d) + \chi_s/\chi_b}{\chi_b - \chi_a\chi_s/\chi_b - \mathrm{ctg}(k_{z,b}d)(\chi_a + \chi_s)}, \quad \chi_{a(b)} = \varepsilon_{a(b)}\frac{k_0}{k_{z,a(b)}}, \quad \chi_s = \varepsilon_s\frac{k_0}{k_{z,s}} + Z_0\sigma(\omega)$$

Induced electric field in the ambient medium:

$$\mathbf{E}_a^{(ind)}(x,z) = \mathbf{E}_0^{(r)}\exp(ik_0 z) + \int_{-\infty}^{+\infty}\mathbf{E}_a^{(sc)}(k_0)\exp(ik_x x + ik_{z,a}z)dk_x, \quad k_{z,a(s)} = \sqrt{k_0^2\varepsilon_{a(s)} - k_x^2}, \quad k_0 = \omega/c$$

Total electric field in the substrate:

$$\mathbf{E}_s(x,z) = \mathbf{E}_0^{(t)}\exp[-ik_0\sqrt{\varepsilon_s}(z+d)] + \int_{-\infty}^{+\infty}\mathbf{E}_s^{(sc)}(k_x)\exp\left[ik_x x - ik_{z,s}(z+d)\right]dk_x$$

Characteristic Electromagnetic Lengths of Partially Gated 2D Electron Channel: Definitions

Scattering Length:

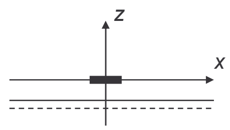
$$L^{(sc)}_{a(s)} = \frac{P_{a(s)}}{P_0} \qquad L^{(sc)} = L^{(sc)}_a + L^{(sc)}_s$$

Absorption Length:

$$L^{(ab)} = \frac{Q}{P_0}$$

$$Q = 2\pi\,\mathrm{Re}\left\{\sigma(\omega)\sqrt{\varepsilon_s}\left[\mathbf{E}_0^{(t)}\right]^*\mathbf{E}_s^{(sc)}(k_x=0)\right\} + \pi\,\mathrm{Re}\{\sigma(\omega)\}\int_{-\infty}^{+\infty}\left|\mathbf{E}_s^{(sc)}(k_x)\right|^2 dk_x$$

$$P_{a(s)} = \frac{\pi}{Z_0}\int_{-k_0\sqrt{\varepsilon_{a(s)}}}^{k_0\sqrt{\varepsilon_{a(s)}}} \mathbf{n}_{a(s)}\frac{\mathbf{k}_{a(s)}}{k_0}\left|\mathbf{E}^{(sc)}_{a(s)}(k_x)\right|^2 dk_x$$



Extinction Length:

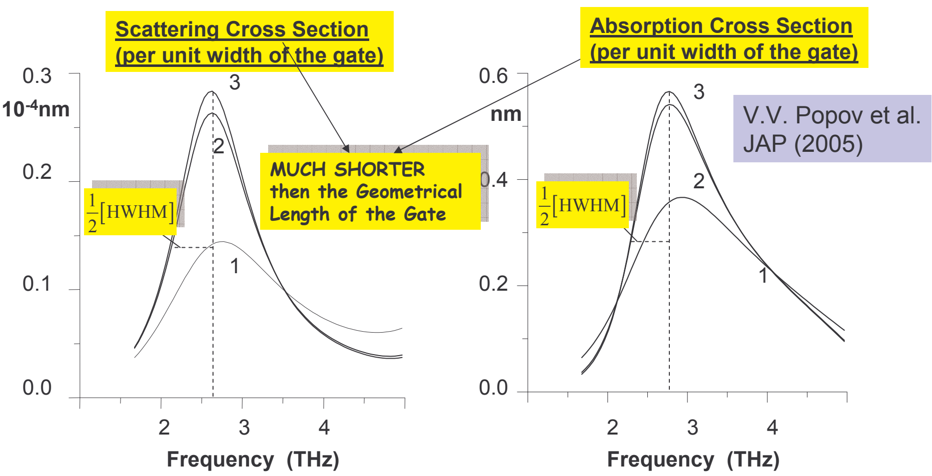
Energy conservation low $L^{(ex)} = L^{(sc)} + L^{ab}$

$$L^{(ex)} = \frac{4\pi}{|E_0|^2}\mathrm{Re}\left\{\sqrt{\varepsilon_a}\left[\mathbf{E}_0^{(r)}\right]^*\mathbf{E}_a^{(sc)}(k_x=0) + \sqrt{\varepsilon_s}\left[\mathbf{E}_0^{(t)}\right]^*\mathbf{E}_s^{(sc)}(k_x=0)\right\}$$

Optical theorem

V.V. Popov et al., JAP (2005)

THz Scattering and Absorption by Gated Plasmons in a Single-Channel HEMT

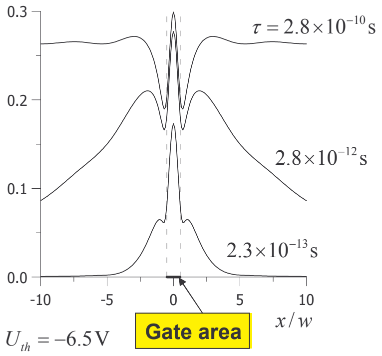


$U_{th} = -1.17\,\mathrm{V}$, $U_g = -1\mathrm{V}$ $(N_s = 4.386\times10^{11}\,\mathrm{cm}^{-2})$, $m^* = 0.042\,m_0$, $w = 60\,\mathrm{nm}$, $d = 10\,\mathrm{nm}$, $\varepsilon_s = \varepsilon_b = 13.88$

$\tau = 2.3\times10^{-13}\,\mathrm{s}$ (curve 1); 2.8×10^{-12} (curve 2); 2.8×10^{-10} (curve 3) $\longrightarrow$ $\frac{1}{2\pi\tau} < 10^{-3}\,\mathrm{THz}$

Leakage of Gated Plasmons into Ungated Regions of 2D Channel

In-plane electric field distribution in the channel (arb. units):



$U_{th} = -6.5\,\text{V}$

$U_g = -5.54\,\text{V}$ (N=$4.386\times10^{11}\,\text{cm}^{-2}$)

$m^* = 0.042\, m_0$

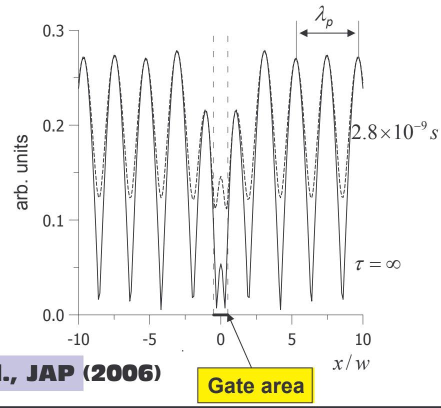
$w = 400\,\text{nm}$

$d = 167\,\text{nm}$

$\varepsilon_s = \varepsilon_b = 13.88$

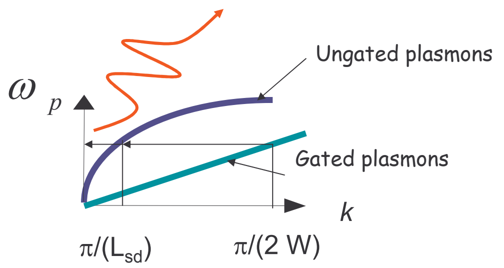
$$\omega^2 = \frac{e^2 N}{2\bar{\varepsilon}\varepsilon_0 m^*}k, \qquad k = \frac{2\pi}{\lambda_p}$$

$$\bar{\varepsilon} = \frac{1}{2}\left[\varepsilon_s + \varepsilon_b \frac{1+\varepsilon_b \tanh(kd)}{\varepsilon_b + \tanh(kd)}\right]$$

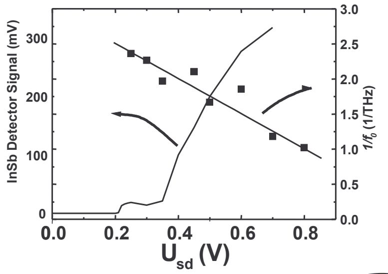


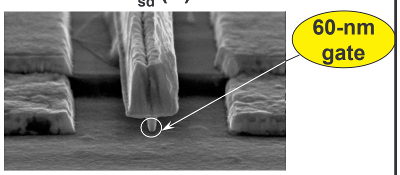
V.V. Popov et al., JAP (2006)

THz Generation in Nanometer-Gate HEMT via Gated-Ungated Plasmon Interaction



Knap W. et al, APL (2004)
IEEE Spectrum (May 2004)

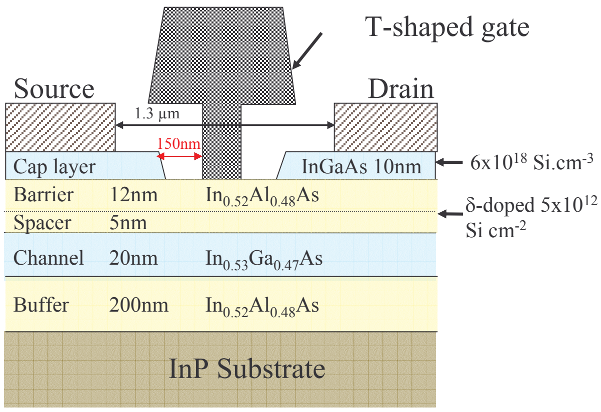




The most efficient THz generation occurs when BOTH the ungated and gated plasmons are in resonance

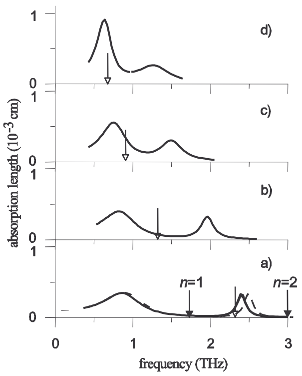
InGaAs 60-nm-wide gate HEMT (Courtesy of W. Knap)

A Single-Gate InGaAs/InAlAs HEMT

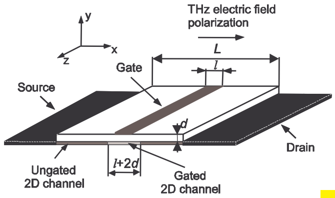


Parenty et al., Proc IPMR Conf., Nara 2001, p. 626 - 629

Tunable Screening of Inter-Contact Plasmons by a Recessed Gate



width of the gate strip (nm):
200 (a), 400(b), 600 (c) and 800 (d)

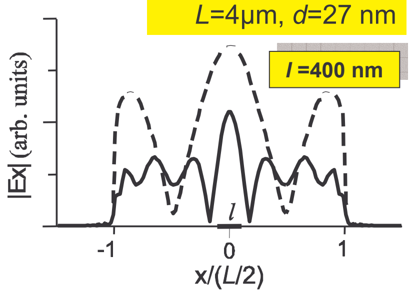


$$n_s^{(g)} = 1\times10^{12}\ \mathrm{cm}^{-2}$$

$$n^{(un)} = 3\times10^{12}\ \mathrm{cm}^{-2}$$

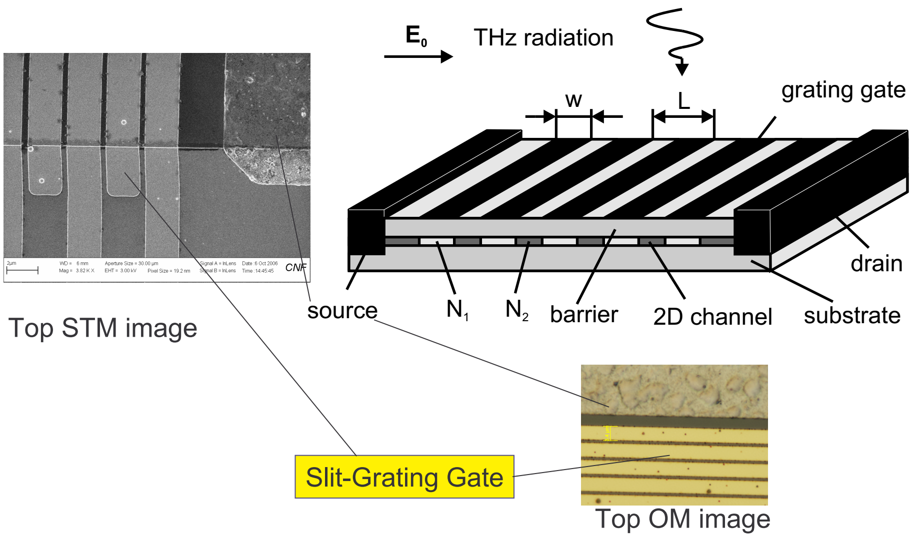
$$\tau = 2.3\times10^{-12}\ \mathrm{s}$$

L=4µm, d=27 nm



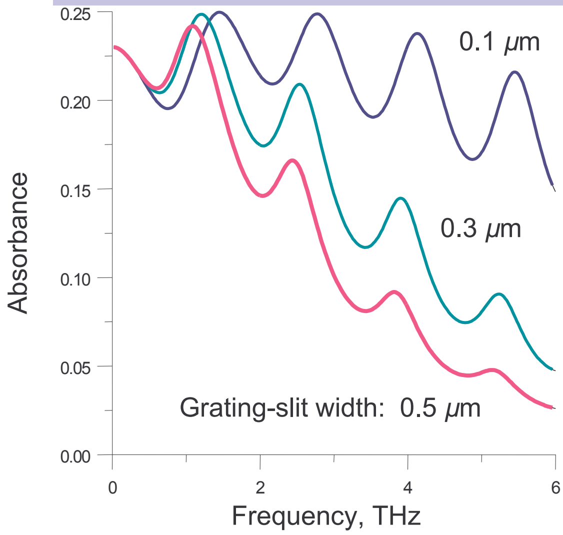
$$\omega_p^{(g)} = \frac{\pi(2n-1)}{l_{eff}}\sqrt{\frac{e^2 n^{(g)} d}{m^* \varepsilon_0 \varepsilon_2}}, \qquad l_{eff} = l + 2d$$

FET Structure with a Common Channel and a Large Area Grating-Gate



Plasmon Resonances in a Grating-Gate AlGaN/GaN HEMT

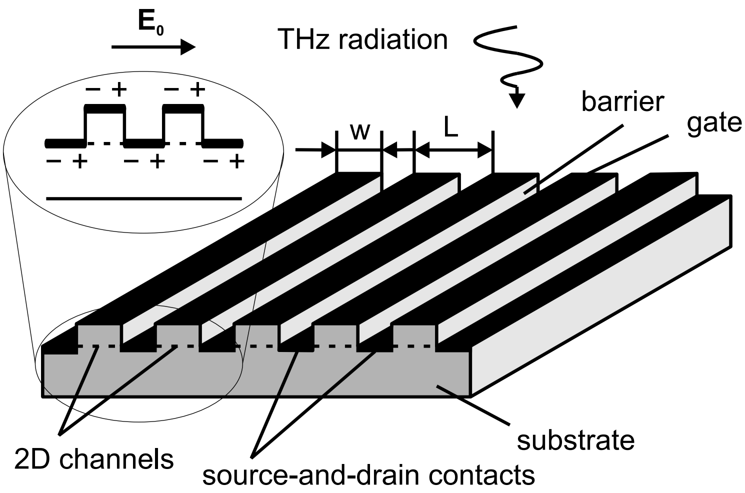
ov et al., Bulletin of the Russian Academy of Sciences: Physics (2007)



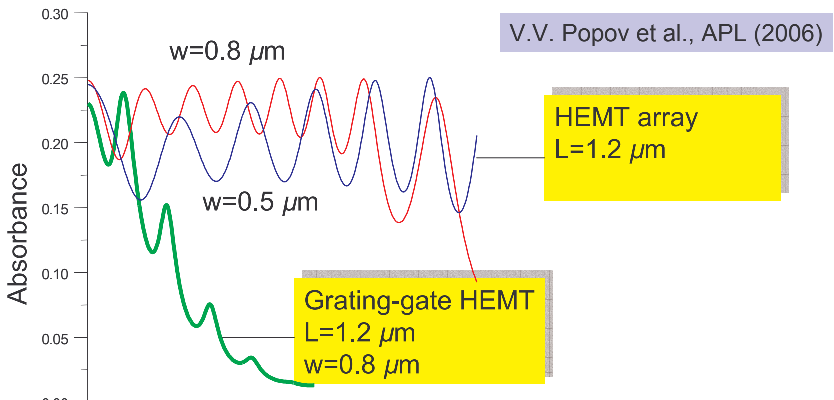
Room temperature

Grating-gate strip width (gate length) is 1 μm

FET Array with Separate Channels



Plasmon Resonances in a AlGaN/GaN HEMT periodic array



Room temperature
μ = 2,000 cm²/ V s

Plasmon absorption per unit area of the array in the model of non-interacting FET units is less then 10^{-3} !!!

Conclusions

- Electromagnetic approach is important to describe plasma oscillations in FET-like microdevices at THz frequencies
- Maximum resonant absorption takes place when the dissipative broadening of the plasma resonance is equal to its radiative broadening
- High-frequency resistance of a slot diode may be measured from contactless measurements of the characteristic electromagnetic lengths of the diode
- Gated plasmons under a sub-micron gate exhibit short scattering length and, therefore, they can not couple effectively to THz radiation
- Gated plasmons interact effectively with ungated plasmons in the access regions of the channel. This phenomenon may be used for coupling the gated plasmons to THz radiation
- Higher-order inter-contact plasmon resonances can be tuned in frequency by a recessed gate
- HEMT arrays is effective for exciting higher-order plasmon modes in the channel due to strong cooperative coupling of plasmons to THz radiation, which makes possible to design THz plasmonic devices with operating frequencies up to 15 THz or even higher

Plasmonic Devices with 2D Electron Channel for THz Applications

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Thank you for your attention!