High-responsivity terahertz detection by on-chip InGaAs/GaAs field-effect-transistor array

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Outline of the Talk

1. Why plasmons are promising for their application at THz frequencies?

2. Antenna properties of a dense FET array

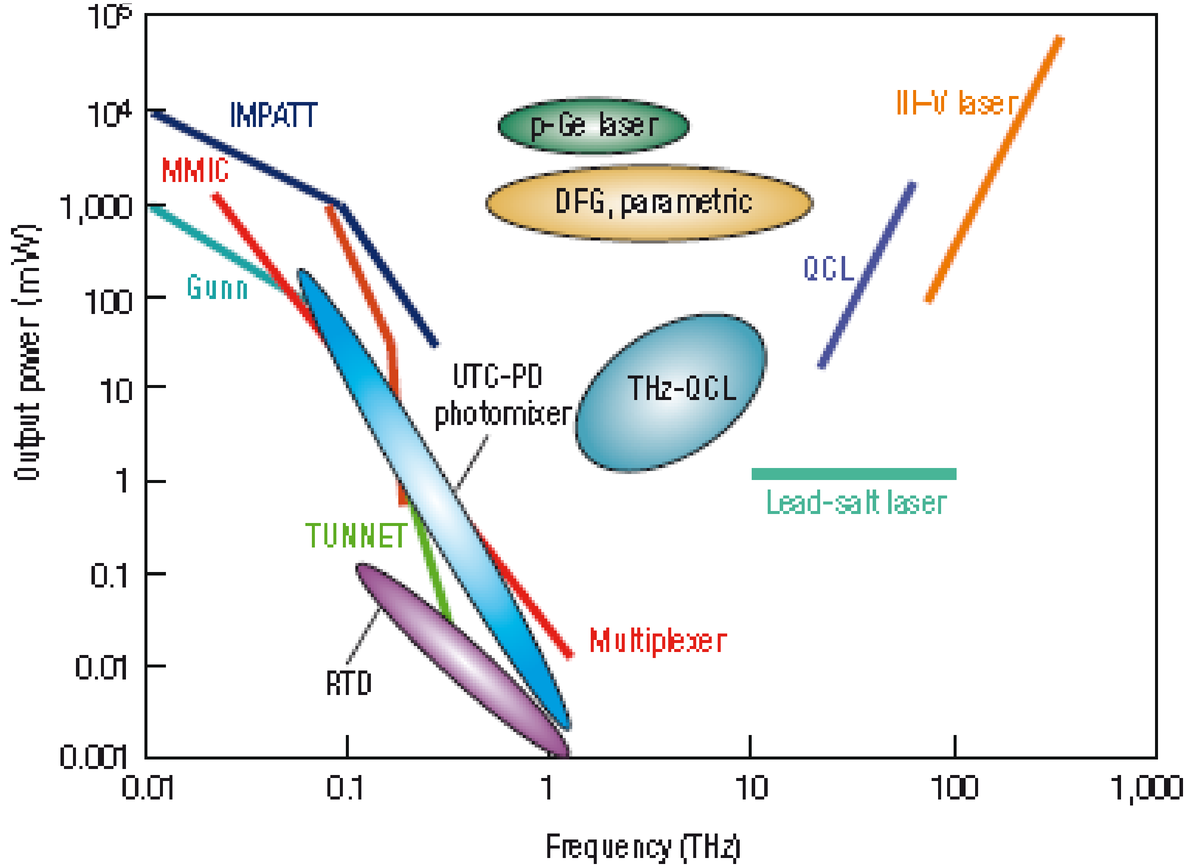
3. Photovoltaic plasmonic THz detection by the FET with an asymmetric gate

4. High-responsivity THz detection by a dense array of FETs with asymmetric gates

5. Conclusions

Terahertz Gap

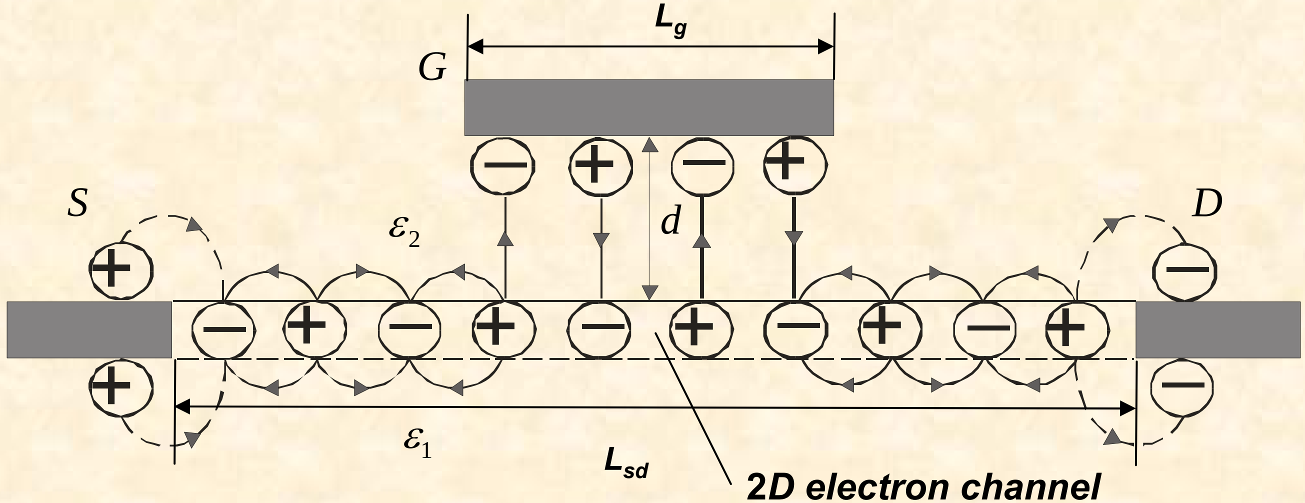
From: M. Tonouchi, Nature Photon. **1**, 97 (2007)



Why Plasmonic Devices Can Be Promising at THz?

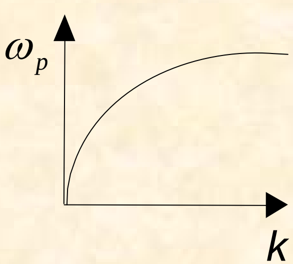
- ✓ **Plasmonic photoresponse occurs at high terahertz frequencies**
- ✓ **Plasmons are classical excitations – free from quantum limitations at terahertz frequencies**
- ✓ **Photoresponse is broadband or widely tunable**
- ✓ **Photoresponse is extremely fast (the plasmon velocity faster then the electron transfer velocity by two orders of magnitude)**
- ✓ **Electrical read-out is possible**

Plasma Oscillations in a Transistor Structure



Ungated 2D plasmons

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



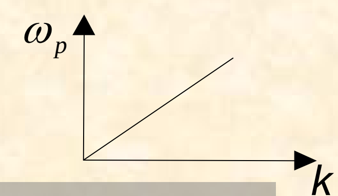
R.H. Ritchie, PR (1957)
F. Stern, PRL (1967)

$$k = \pi n / L_{sd}$$

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

A.V. Chaplik, JETP (1972)

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



Gradual channel approximation:

$$N_{2D} = \frac{\varepsilon_0 \varepsilon}{ed} U_0 ,$$

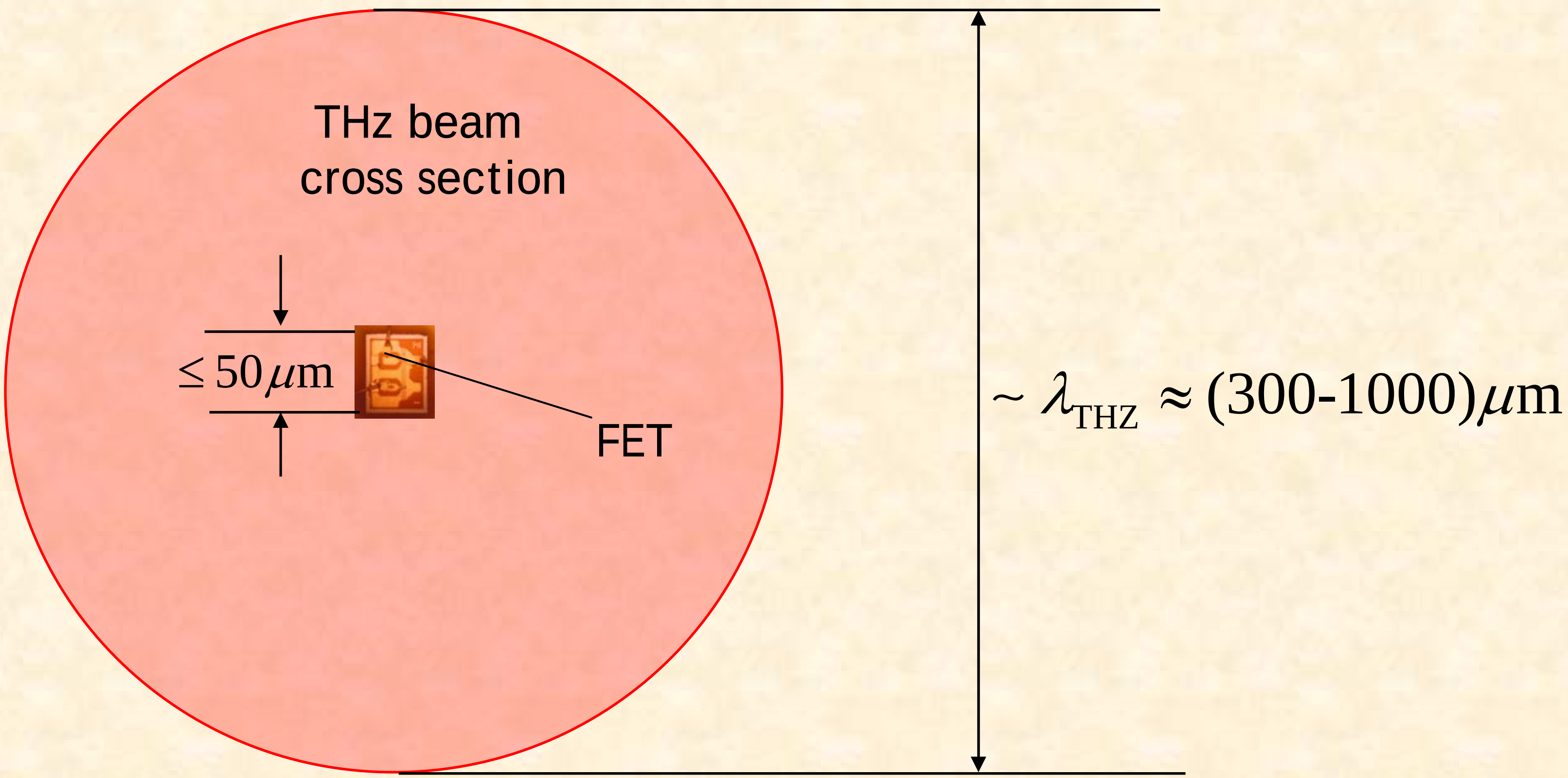
where $U_0 = U_g - U_{th}$

$$\omega_p = sk , \qquad s = \sqrt{\frac{eU_0}{m^*}}$$

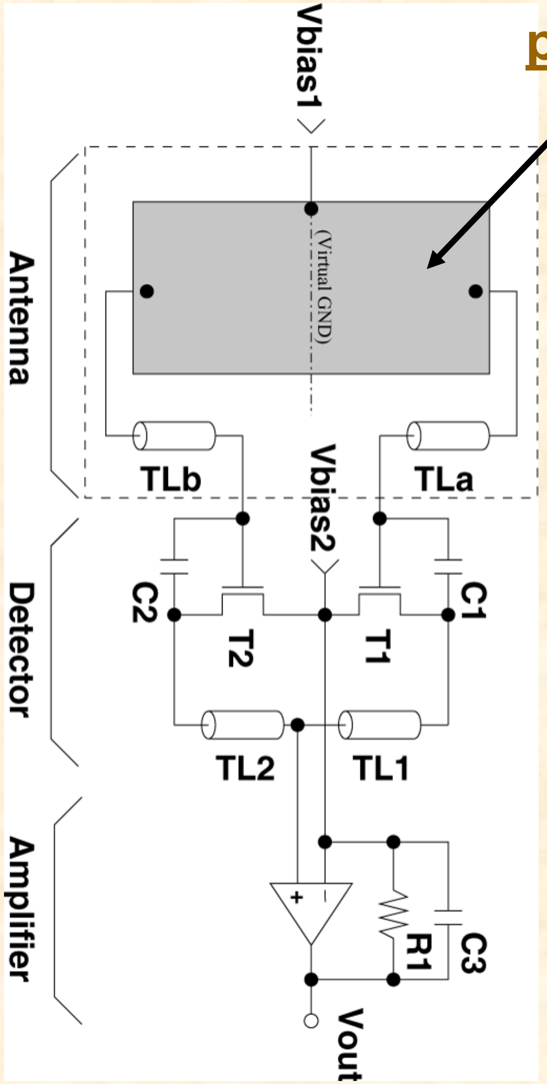
M. Dyakonov, M.Shur
PRL (1993)

$$k = \pi n / L_g$$

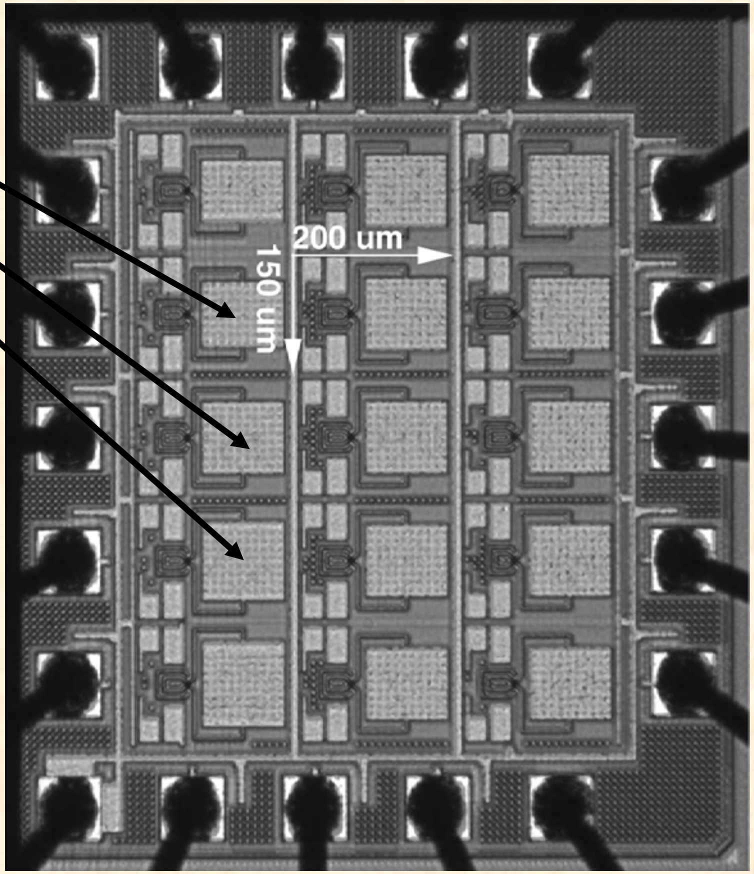
A Single FET Weakly Couples to THz Beam



A Single FET Detector Needs an Antenna Coupler



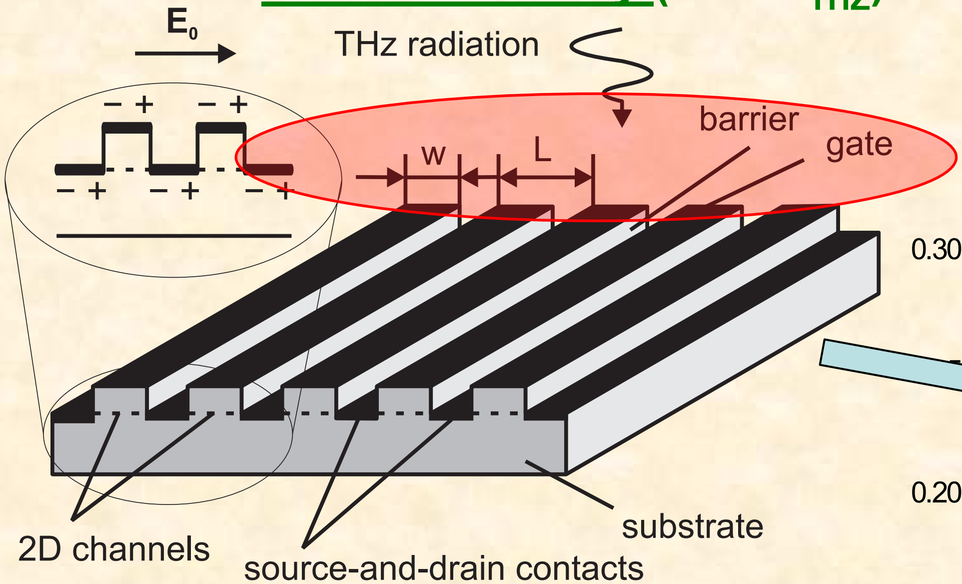
patch antenna



E. Öjefors et al, IEEE J.Solid-State Circuit (2009)

Dense FET Array as a Super-Broadband Antenna

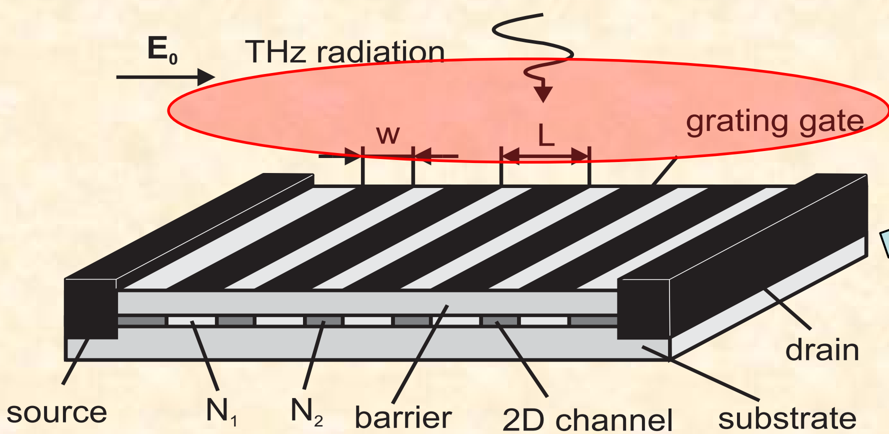
Dense FET array ($L \ll \lambda_{THZ}$)

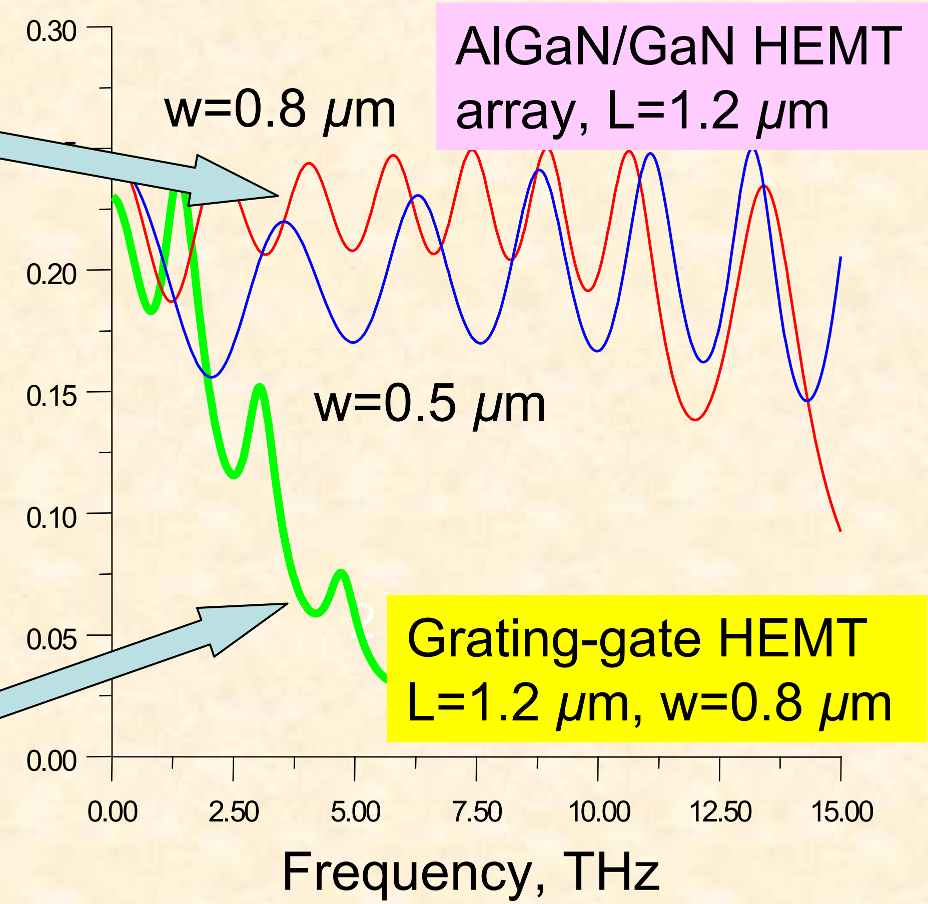


V.V. Popov et al. APL (2006)

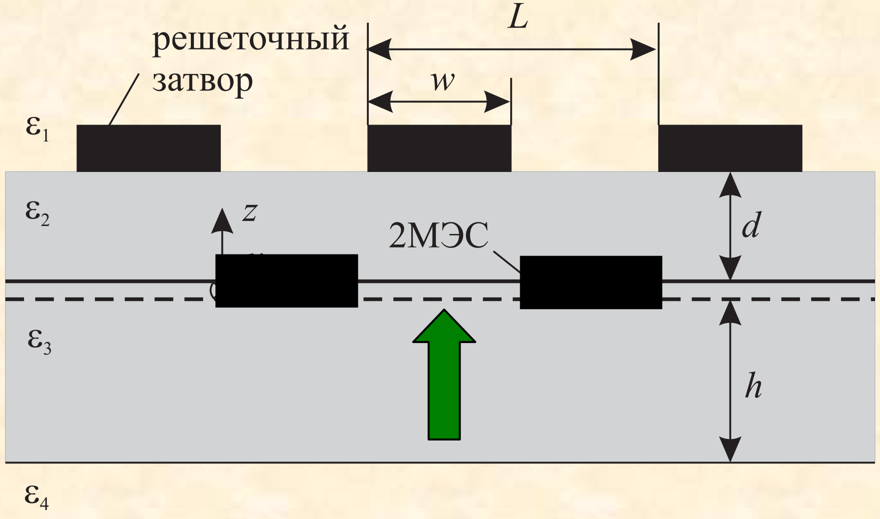
T = 300 K, μ = 2000 cm²/ V s

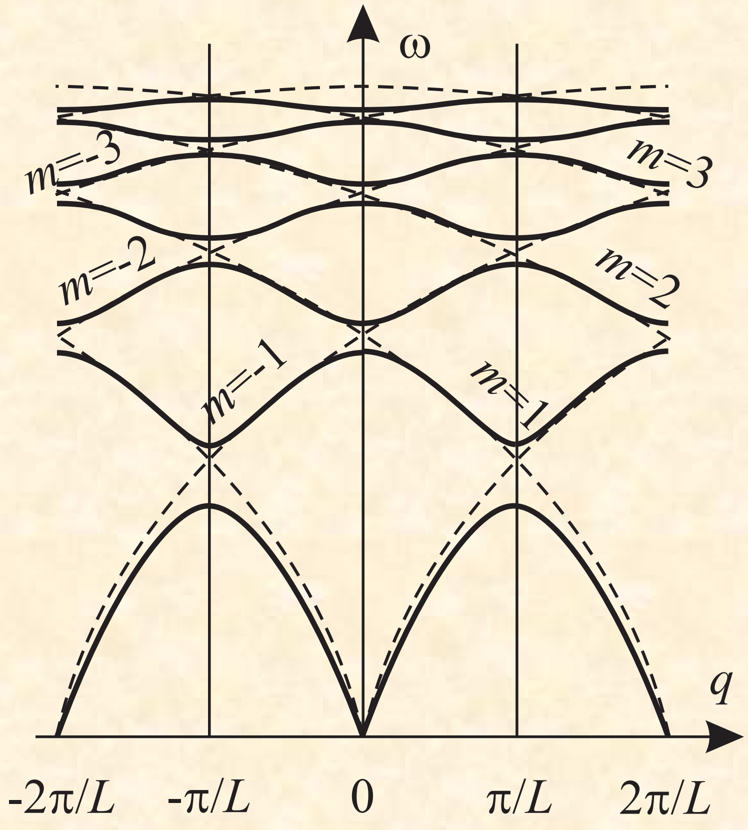
Grating-Gate FET structure



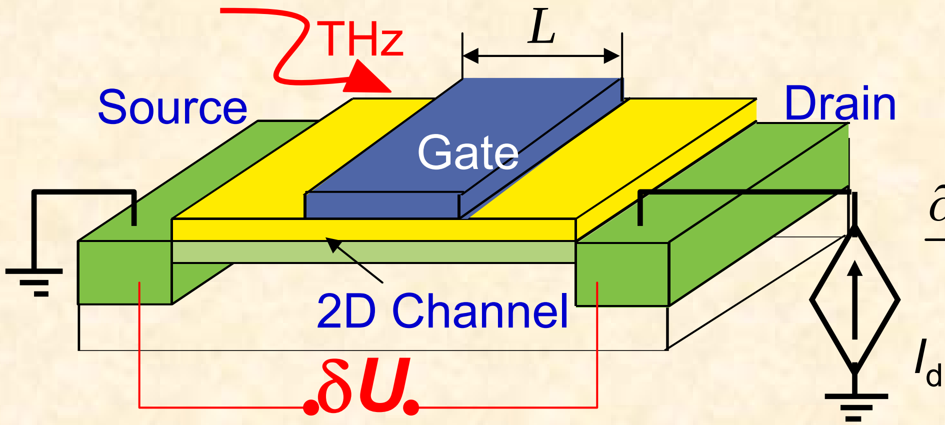


Plasmonic Bandstructure for Periodic FET Array





Terahertz Detection by Plasmons



Hydrodynamic equations:

$$\frac{\partial V(x)}{\partial t} + V(x)\frac{\partial V(x)}{\partial x} + \frac{V(x,t)}{\tau} = -\frac{e}{m^*}E(x)$$

$$\frac{\partial}{\partial t}N(x) + \frac{\partial}{\partial x}[N(x)V(x)] = 0$$

Resonant detection: $\omega\tau_p > 1$

$$\delta U(L) \approx \frac{U_a^2}{4U_0}\frac{\omega_0^2}{(\omega-\omega_0)^2 + \left(\frac{1}{2\tau} - \frac{v_d}{L}\right)^2}$$

dc bias reduces plasma wave damping

$$U_0 = U_g - U_{th}$$

Non-resonant detection: $\omega\tau_p < 1$

τ_p is the PLASMON relaxation time

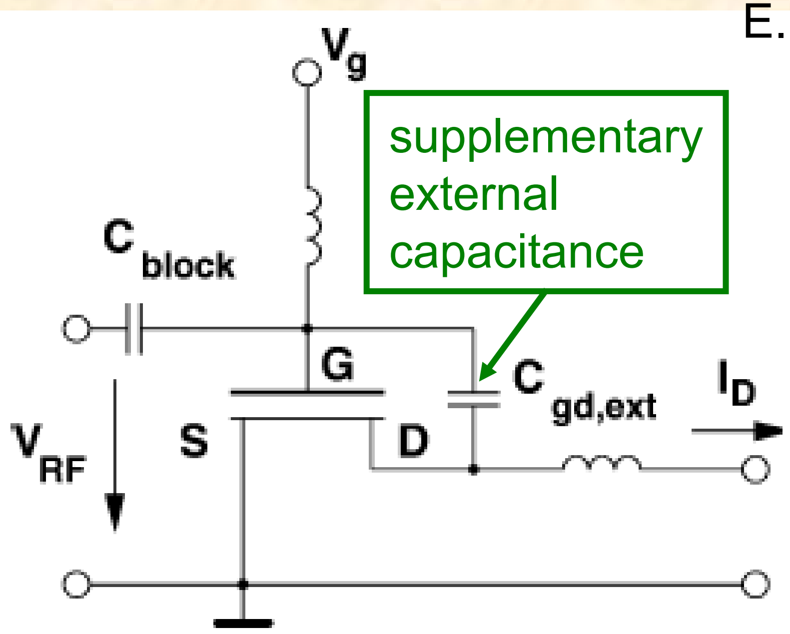
$$\delta U(L) \approx \frac{U_a^2}{4U_0}\frac{1}{\sqrt{1 - j_d / j_{sat}}}$$

dc bias increases the detection amplitude

D. Veksler et al. PRB (2006)

Resistive Mixing (Detection) with a Triode

E. Öjefors et al, IEEE J.Solid-State Circuit (2009)



$$i_{\rm ds}(t) = v_{\rm ds}(t) g_{\rm ds}(t) = v_{\rm RF}(t) g_{\rm ds}(t)$$

$$g_{\rm ds}(t) = \frac{W}{L}\mu C_{\rm ox}(v_{\rm gs}(t) - V_{\rm th} - v_{\rm ds}/2)$$
$$= \frac{W}{L}\mu C_{\rm ox}(v_{\rm RF}(t)/2 + V_g - V_{\rm th})$$

$$i_{\rm ds}(t) = \frac{W}{L}\mu C_{\rm ox}(v_{\rm RF}(t)^2/2 + v_{\rm RF}(t)(V_g - V_{\rm th}))$$

$$v_{\rm gs}(t) = v_{\rm RF}(t) + V_g$$

$$v_{\rm ds}(t) = v_{\rm RF}(t)$$

при $v_{\rm RF}(t) = V_{\rm RF}\sin(\omega t)$

photocurrent:

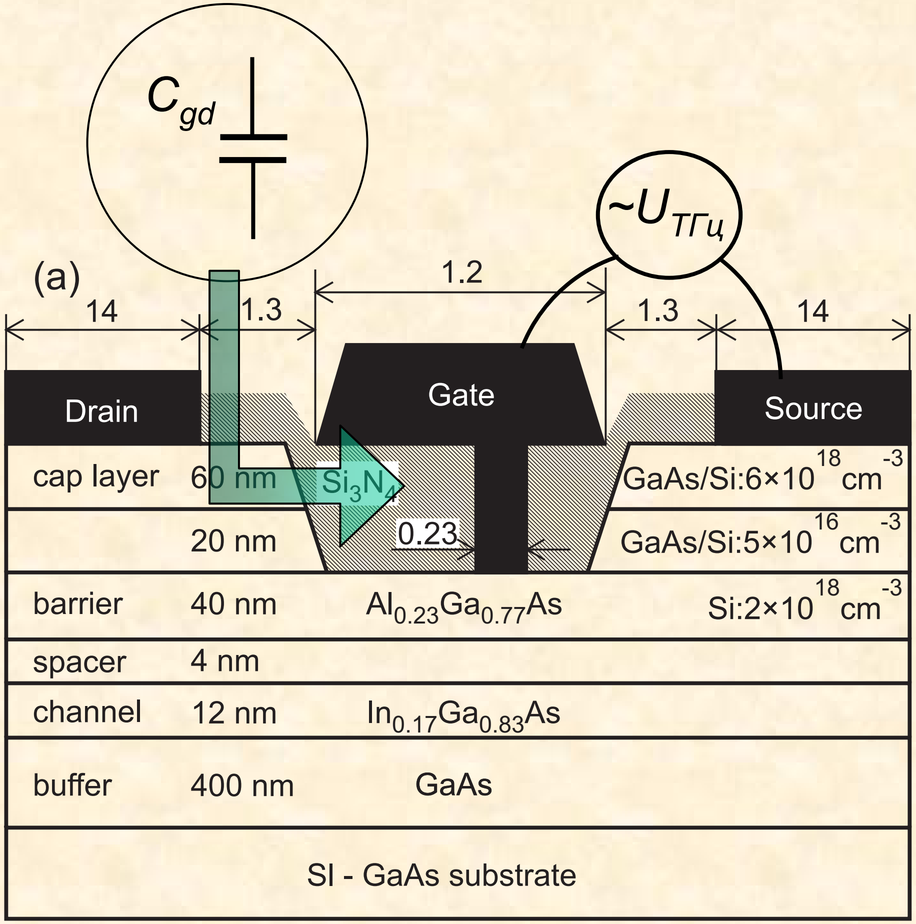
$$I_{\rm ds} = \frac{W}{L}\mu C_{\rm ox} V_{\rm RF}^2/4$$

↔

photovoltage:

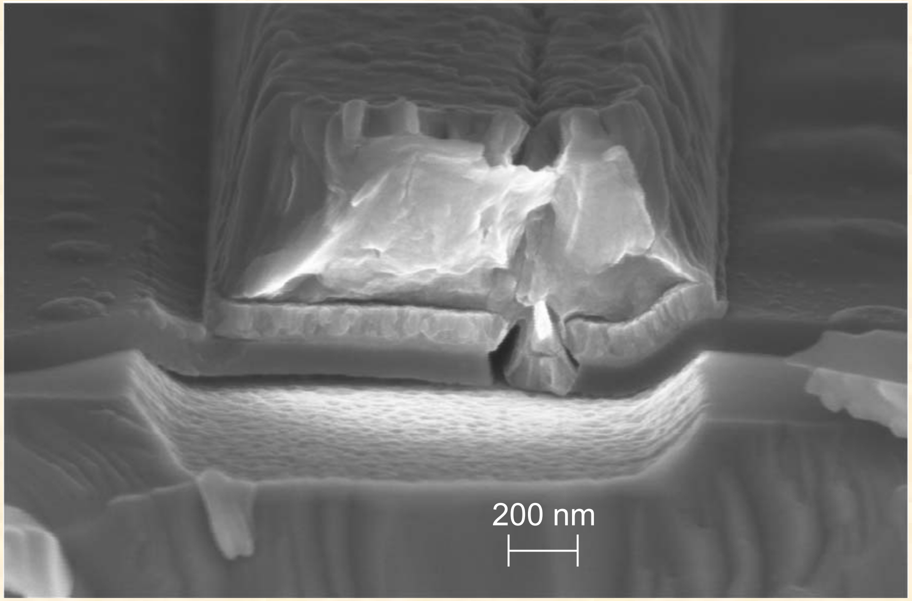
$$V_{\rm ds} = \frac{I_{\rm ds}}{G_{\rm ds}} = \frac{V_{\rm RF}^2}{4(V_g - V_{\rm th})}$$

InGaAs/GaAs FET with Asymmetric Gate



NO supplementary lumped electrical elements needed for ensuring the photovoltaic detection**:**
ALL provided by the build-in design

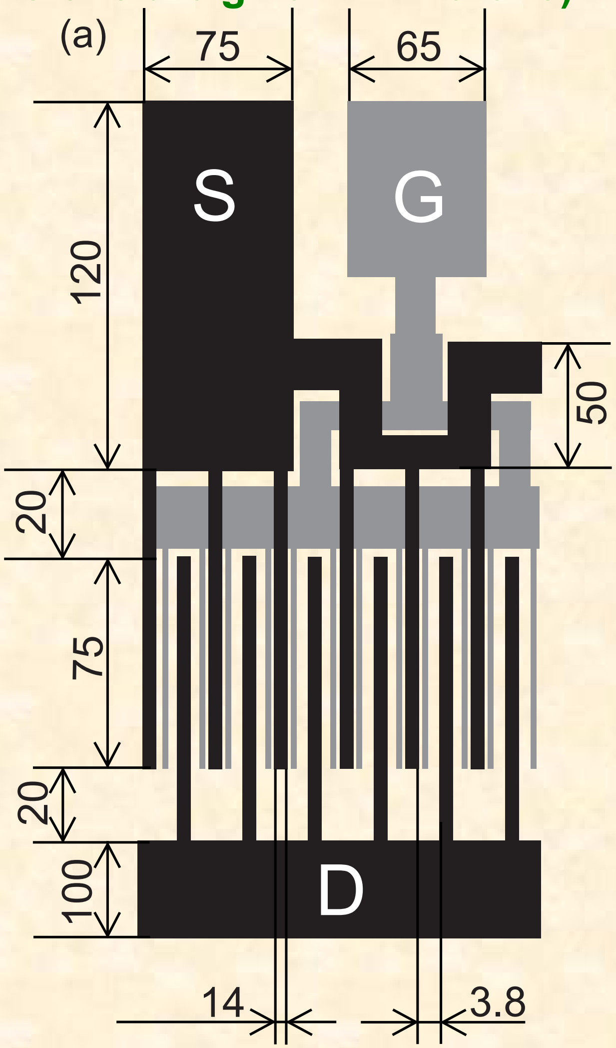
(b)



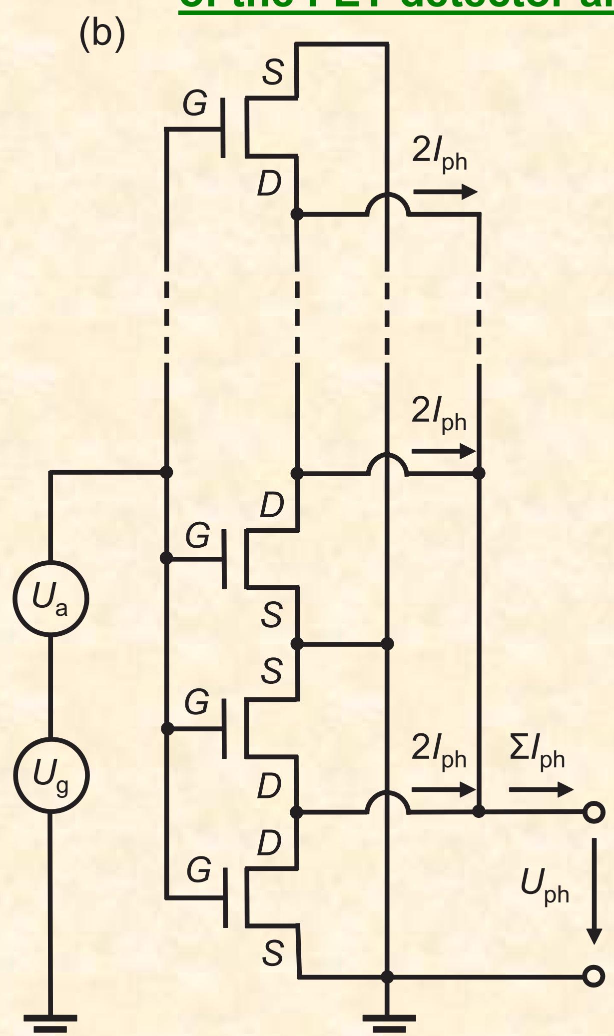
lateral dimensions are given in microns

Parallel Array of FETs with Asymmetric Gates

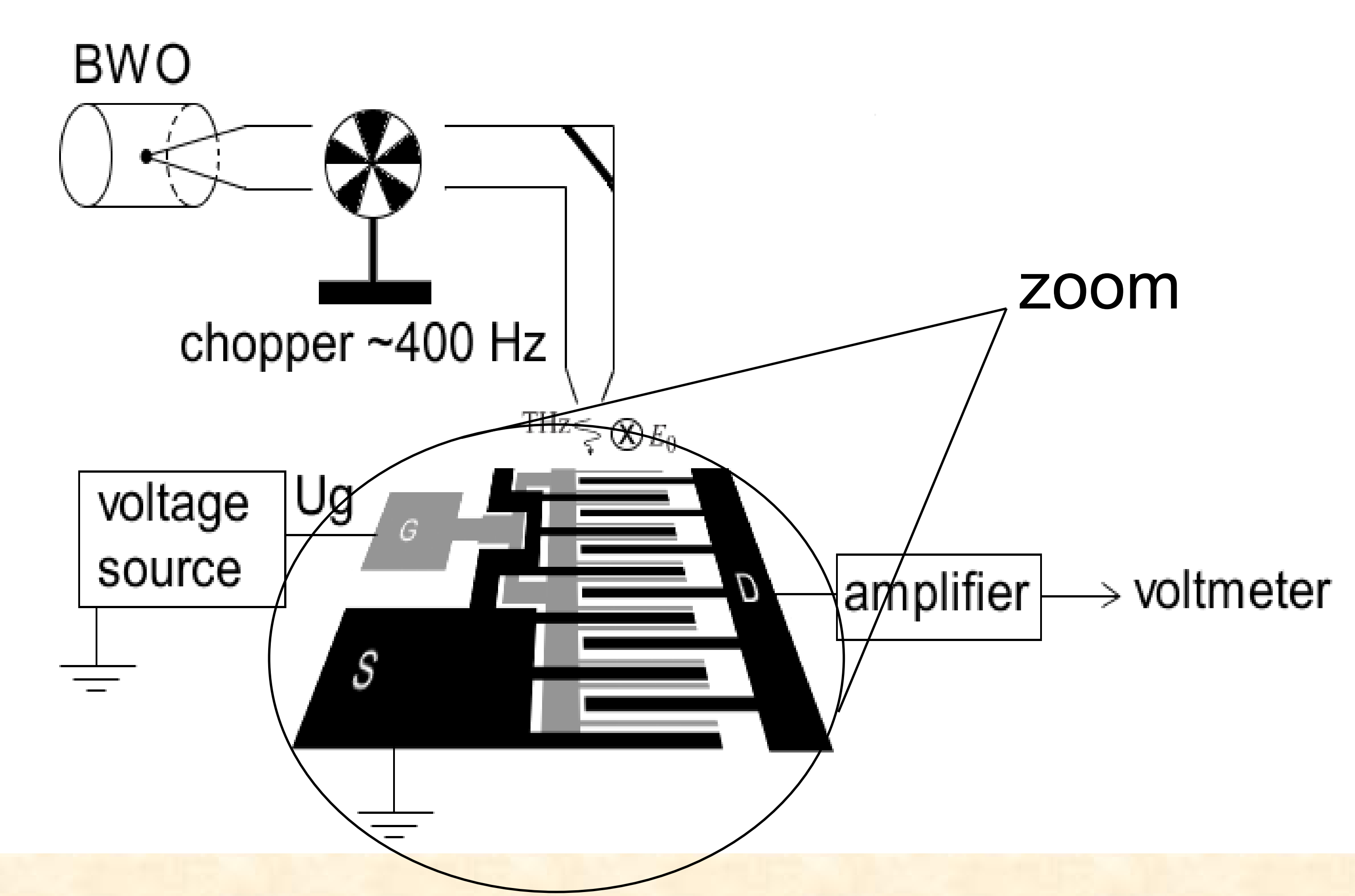
Top view of the unit cell of FET array
(all dimensions are given in microns)



Electrical circuit implementation of the FET detector array

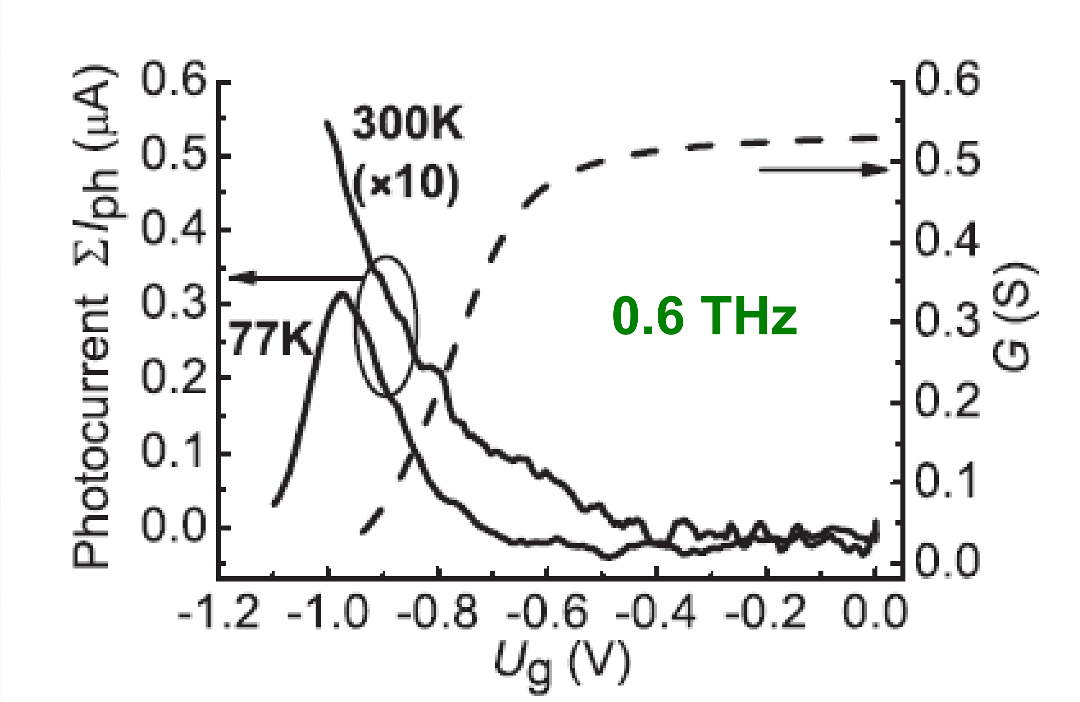


Experimental Setup



Plasmonic Detection in an Array of FETs with Asymmetric Gates

V.V. Popov, D.M. Ermolaev, K.V. Maremyanin, N.A. Maleev, V.E. Zemlyakov, V.I. Gavrilenko, S.Yu. Shapoval, Appl. Phys. Lett. (2011)



Responsivity of the entire array: 0.5 V/W, 0.05 A/W @ 0.6 THz

Responsivity per a FET: 960 V/W, 0.05 A/W @ 0.6 THz

Conclusions

- Dense FET array provides strong super-broadband coupling of THz radiation to plasma oscillations in the FET channels
- A FET with an asymmetric gate can exhibit strong photovoltaic Thz response without supplementary lumped electrical elements
- InGaAs/GaAs FETs with asymmetric gates arranged in a dense array demonstrate record responsivity up to 1kV/W at room temperature
- Super-broadband THz detection is possible in a dense FET array

Relevant papers:

1. V.V. Popov, G.M. Tsymbalov, D.V. Fateev, M.S. Shur, Cooperative absorption of terahertz radiation by plasmon modes in an array of field-effect transistors with two-dimensional electron channel, Appl. Phys. Lett. **89**, 123504 (2006).

2. V.V. Popov, G.M. Tsymbalov, D.V. Fateev, M.S. Shur, Higher-order plasmon resonances in GaN-based field-effect-transistor arrays, Int. J. High Speed Electron. and Systems **17**, 557 (2007).

3. V.V. Popov, G.M. Tsymbalov, M.S. Shur, Plasma wave instability and amplification of terahertz radiation in field-effect-transistor arrays, J. Phys.: Condensed Matter **20**, 384208 (2008).

4. A.V. Muravjov, D.B. Veksler, V.V. Popov, O.V. Polischuk, N. Pala, X. Hu, R. Gaska, H. Saxena, R.E. Peale, M.S. Shur, Temperature dependence of plasmonic terahertz absorption in grating-gate gallium-nitride transistor structures, Appl. Phys. Lett. **96**, 042105 (2010).

5. V.V. Popov, D.M. Ermolaev, K.V. Maremyanin, N.A. Maleev, V.E. Zemlyakov, V.I. Gavrilenko, and S.Yu. Shapoval, High-responsivity terahertz detection by on-chip InGaAs/GaAs field-effect-transistor array, Appl. Phys. Lett. **98**, 153504 (2011).

Thank you for your attention!