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RESONANT TERAHERTZ PHOTOMIXING DEVICES BASED ON INTEGRATION OF QWIP AND HEMT UTILIZING PLASMA EFFECTS

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Outline

- Motivation
- Plasma oscillations in heterostructures
- HEMT photomixer utilizing interband photoexcitation of electrons and holes
- HEMT-QWIP photomixer utilizing intersubband electron photoexcitation by infrared signals: Structure and Principle of operation
- Characteristics of HEMT-QWIP photomixer
- Monte-Carlo modeling
- Conclusions

Motivation

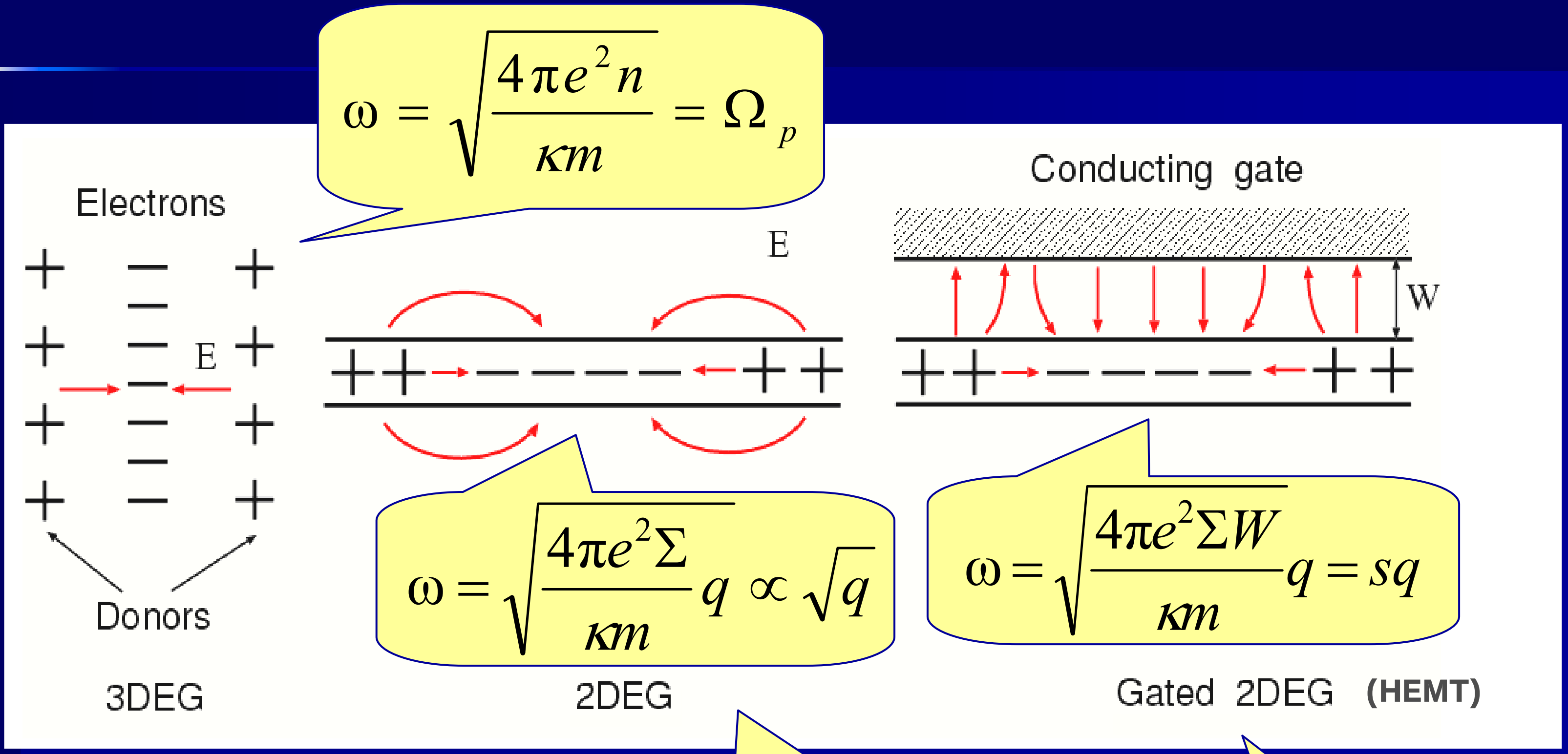
There is strong demand in compact efficient tunable sources and detectors of terahertz radiation.

Mixing of optical signals (photomixing) – radiation of two lasers with close frequencies or ultrashort optical pulses – can effectively stimulate generation of terahertz radiation.

Plasma effects in HEMTs associated with self-consistent oscillations of electron density and electric field result in resonant response.

QWIPs can exhibit fast transformation of incoming infrared signals into electric signals.

Plasma oscillations in 3D- and 2D- electron systems



“Deep-water” wave spectrum

Sound-like “shallow-water” wave spectrum

n – electron 3D concentration

Σ – electron 2D (sheet) concentration in the channel

m – electron effective mass

q – wave number

s – wave velocity

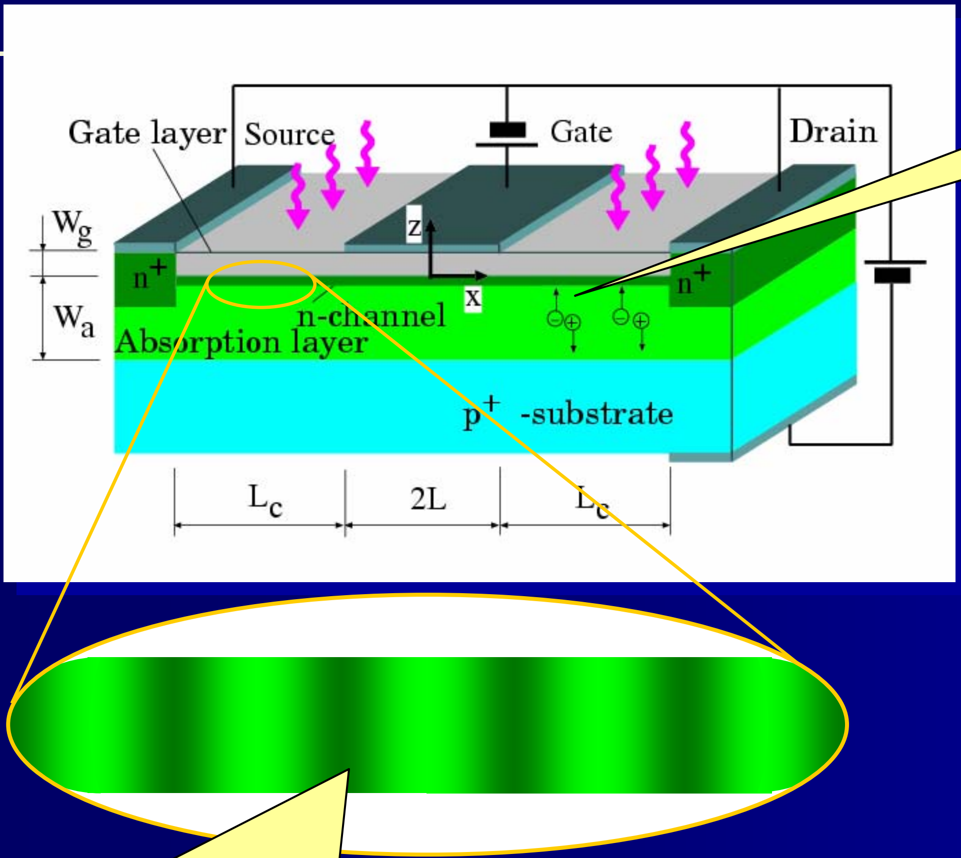
Plasma waves in HEMT-like heterostructures

- Dispersion law $\omega = sq$ - sound-like wave
- Wave velocity $s = \sqrt{\dfrac{4\pi e^2 \Sigma W}{\kappa m}} = \sqrt{\dfrac{eV}{m}}$

  $s \propto \sqrt{\Sigma}, \quad s \cong 10^8\,\mathrm{cm/s}$

- Wave number $q = \dfrac{\pi}{2L} n, \quad n = 1,2,3\ldots$
- Terahertz frequencies for the length of gated region $2L \le 1\,\mu\mathrm{m}$
- Can be used for the detection and generation of terahertz radiation

HEMT resonant photomixer utilizing interband photoexcitation of electrons and holes



Photogenerated electrons and holes

- Optical signals generate electrons and holes in the absorption region
- Built-in electric field accelerates photogenerated electrons and holes
- Propagating electrons and holes induce transient current in the channel which excites plasma oscillations
- Plasma oscillations induce transient charge in contacts and antenna that leads to THz emission

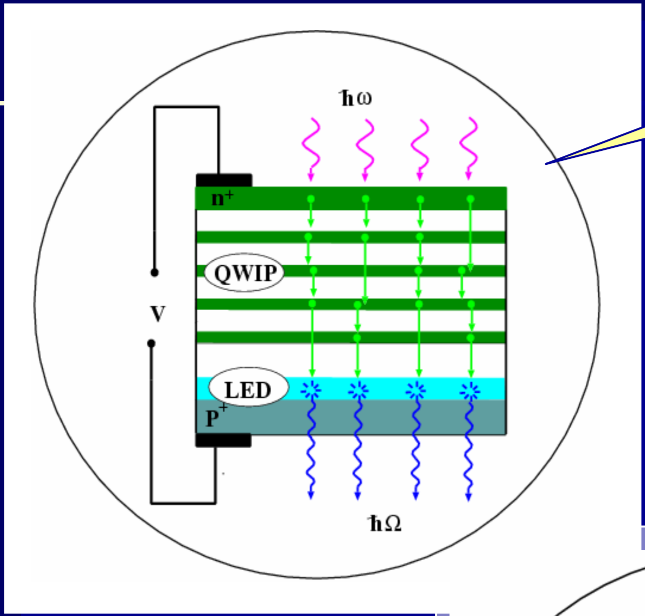
Spatio-temporal modulation of electron density in the channel (plasma oscillations) – HEMT channel serves as resonant cavity

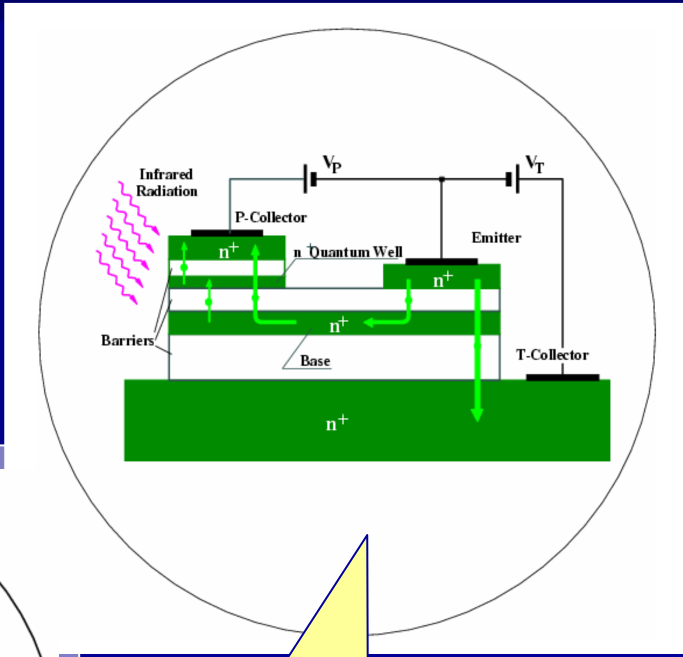
Ryzhii et al. - proposal and theoretical studies

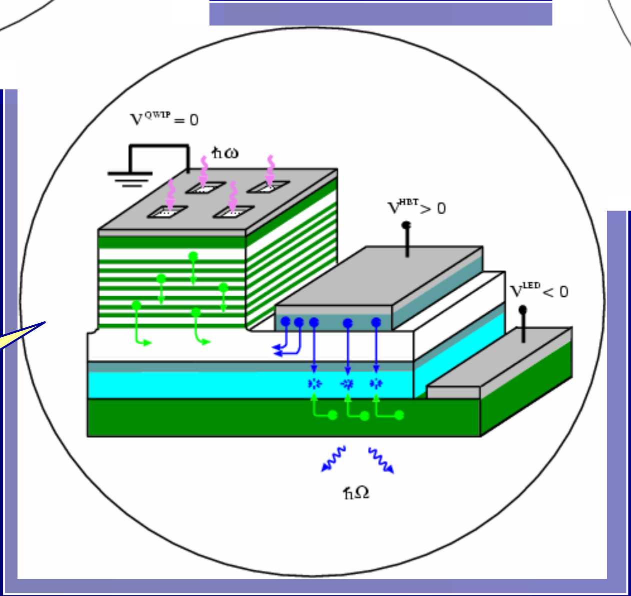
Otsuji et al. – experimental realization

Some integrated QWIP–based infrared devices

QWIP-LED pixel, 1995



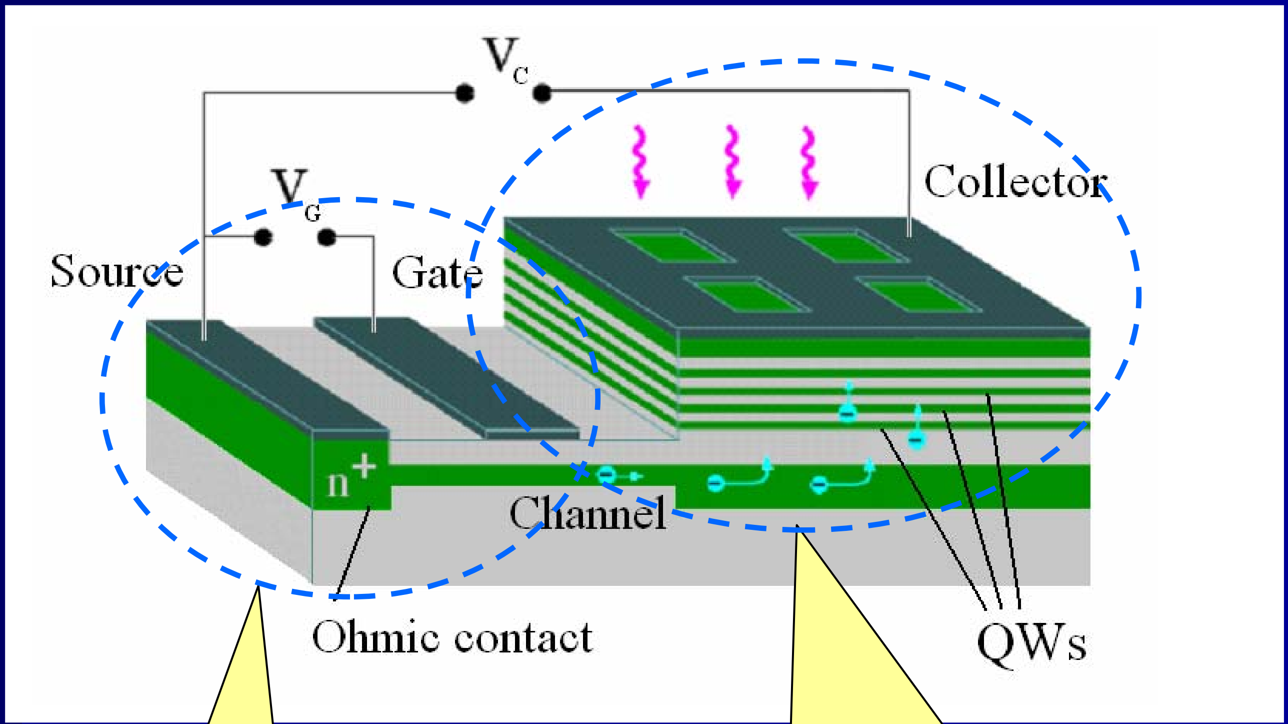




QWIP-HBT-LED pixel, 2003

QWIP-HET – unipolar Darlington infrared phototransistor, 1997

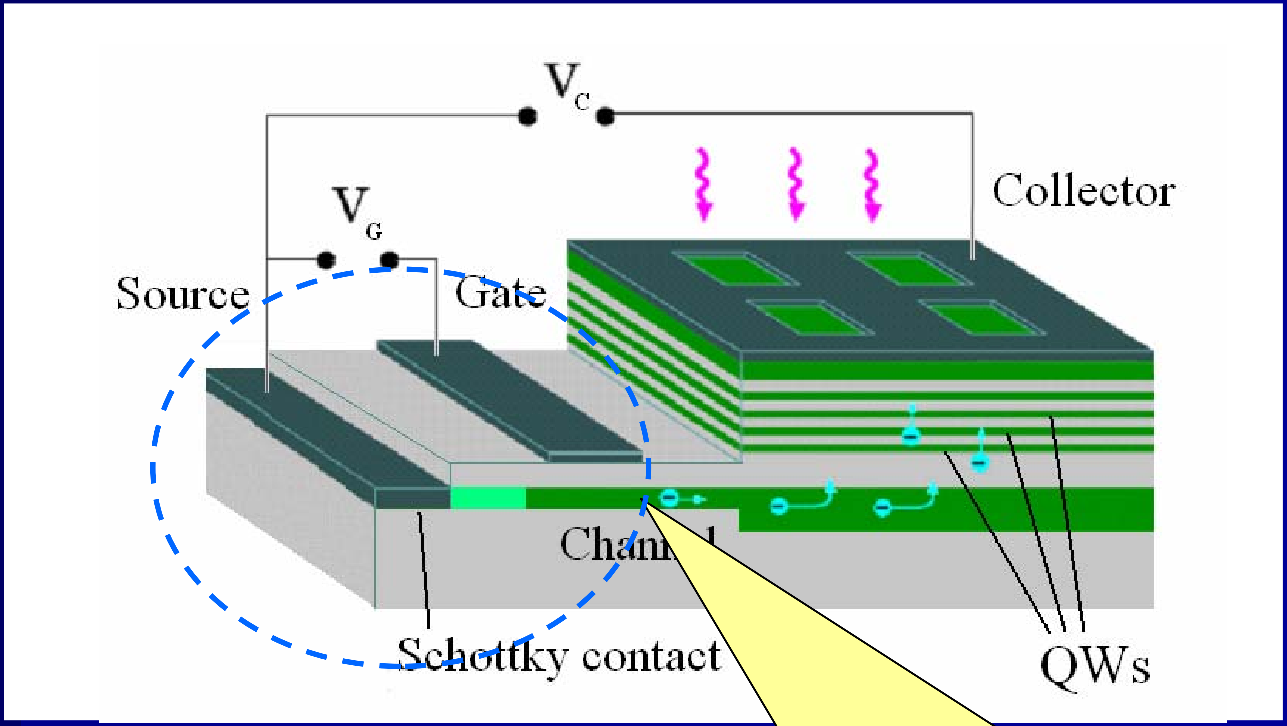
Structures: Resonant photomixer (Infrared-THz converter)



HEMT serves as a resonant cavity

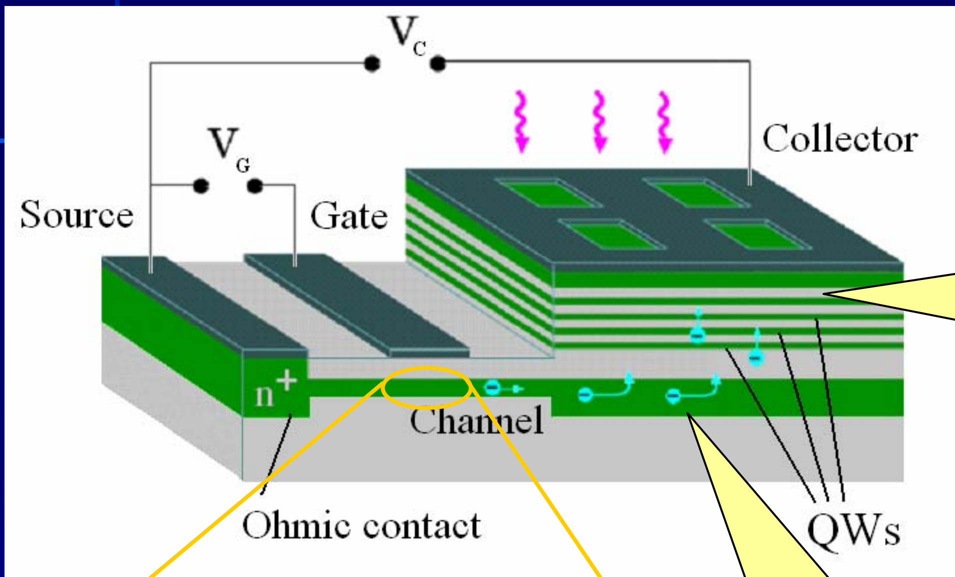
QWIP absorbs infrared signals and transforms them into electric signals

Structures: Resonant THz detector

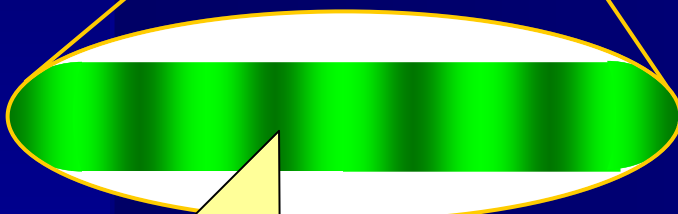


Resonant plasma oscillations can lead to relatively large rectified component of net current

Principle of operation

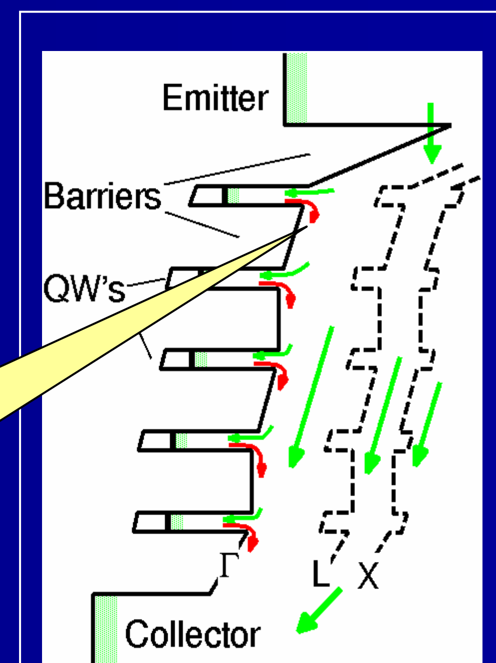


- Infrared signals photoexcite electrons from quantum wells in QWIP (intersubband transitions)
- Electric field accelerates photoexcited electrons



Plasma oscillations in HEMT channel induce transient charges in contacts and antenna – THz emission

Propagating electrons photoexcited from QWs induce the transient current in the channel which, in turn, stimulates the excitation of plasma oscillations.



Photomixer responsivity

HEMT- QWIP responsivity: $\boldsymbol{R}$ [A/W] = $\boldsymbol{J}$ [A] / $\boldsymbol{P}_{\text{Infra}}$ [W]

$$R = R_{\text{HEMT}} R_{\text{QWIP}}$$

$$R_{\text{HEMT}} = \frac{R_0}{\cos[\pi\sqrt{\omega(\omega + i\nu)} / 2\Omega]}$$

Function of signal frequency.

Theory based on HEMT hydrodynamic electron transport model.

$$R_{\text{QWIP}} \cong \frac{\overline{R}(L_{os} / L_{\text{QW}})}{(1 + \omega^2 \tau_{os}^2)}$$

Theoretical (phenomenological) estimate:

τ_{os} is fitting parameter.

Alternative – Ensemble MC particle modeling.

R_0 and $\overline{R}$ are determined by HEMT and QWIP structures, respectively; Ω – characteristic plasma frequency; $\boldsymbol{\nu}$ – electron collision frequency; L_{os}, $\boldsymbol{\tau}_{\text{os}}$ – overshoot length and time in QWIP

$$|R| = \frac{\overline{R}(L_{os} / L_{\text{QW}})}{(1 + \omega^2 \tau_{os}^2)\,|\cos[\pi\sqrt{\omega(\omega + i\nu)} / 2\Omega]|}$$

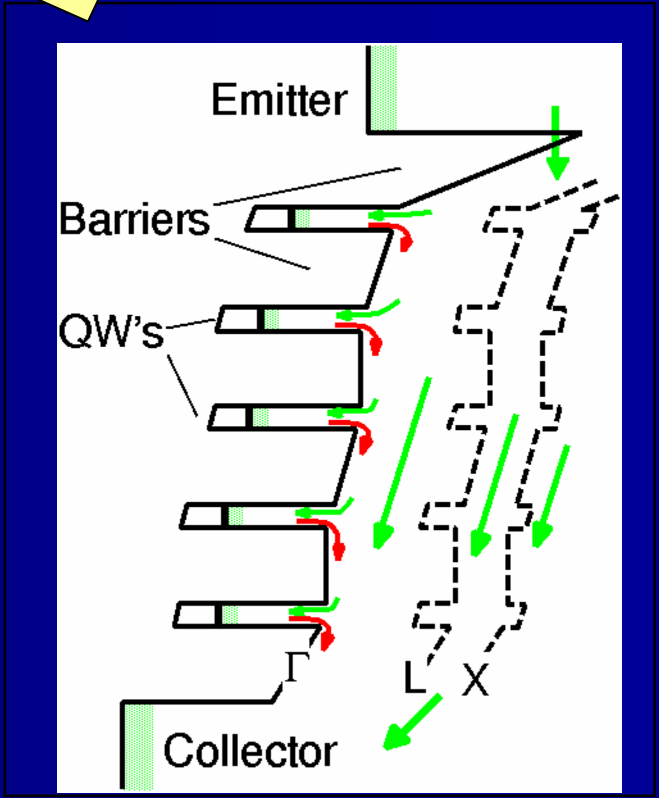
$$\max|R| = \frac{\overline{R}(L_{os} / L_{\text{QW}})}{(1 + \Omega^2 \tau_{os}^2)}\left(\frac{\Omega}{\nu}\right) \cong \overline{R}\left(\frac{L_{os}}{L_{\text{QW}}}\right)\left(\frac{\Omega}{\nu}\right)$$

Ensemble Monte Carlo particle modeling

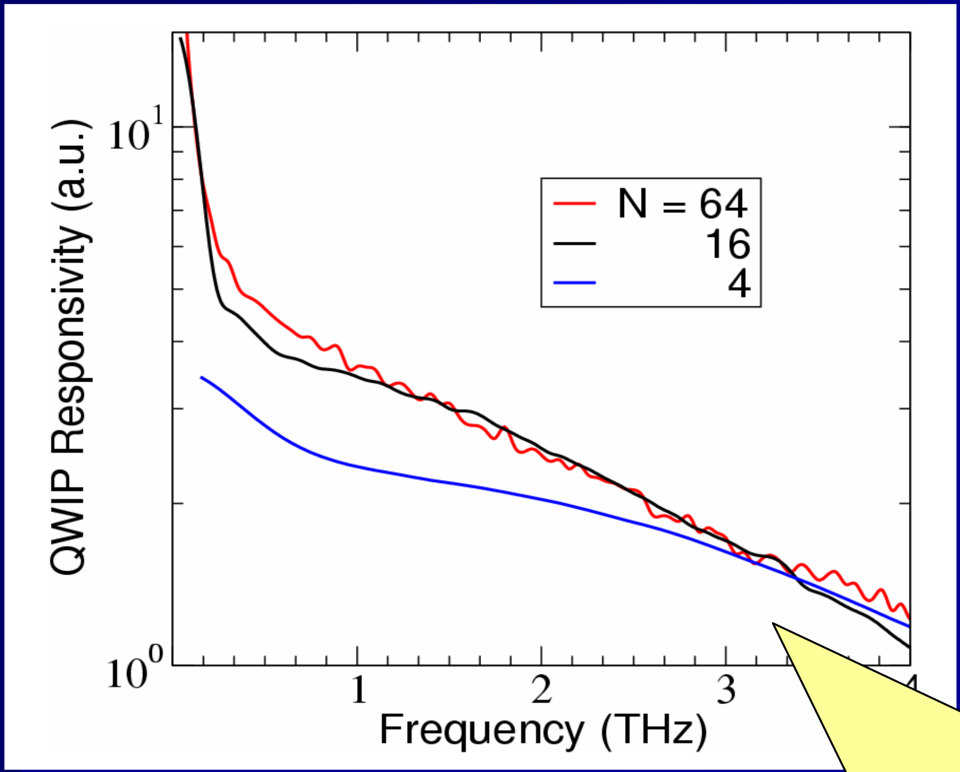
Boltzmann equation for photogenerated electrons + Poisson equation for the self-consistent potential

- Γ, L, and X valleys band model for electrons.
- All essential electron scattering mechanisms, photoexcitation from and capture to QWs.
- Self-consistent electric field.
- Response to delta-like infrared pulse and its Fourier transform
- Photogenerated electrons are created with the energy $\varepsilon_0 = \hbar\Omega_{\text{Infra}} - \Delta$, where $\hbar\Omega_{\text{Infra}}$ is the photon energy, Δ is the QW ionization energy.
- Number of particles – up to 500,000
  Time step Δt = 10 fs,
  spatial mesh size Δz = 2 nm.

T = 77 K
σ = 2x10^{-15} cm^2
Σ_d = 5x10^{12} cm^{-2}
E = 40 kV/cm

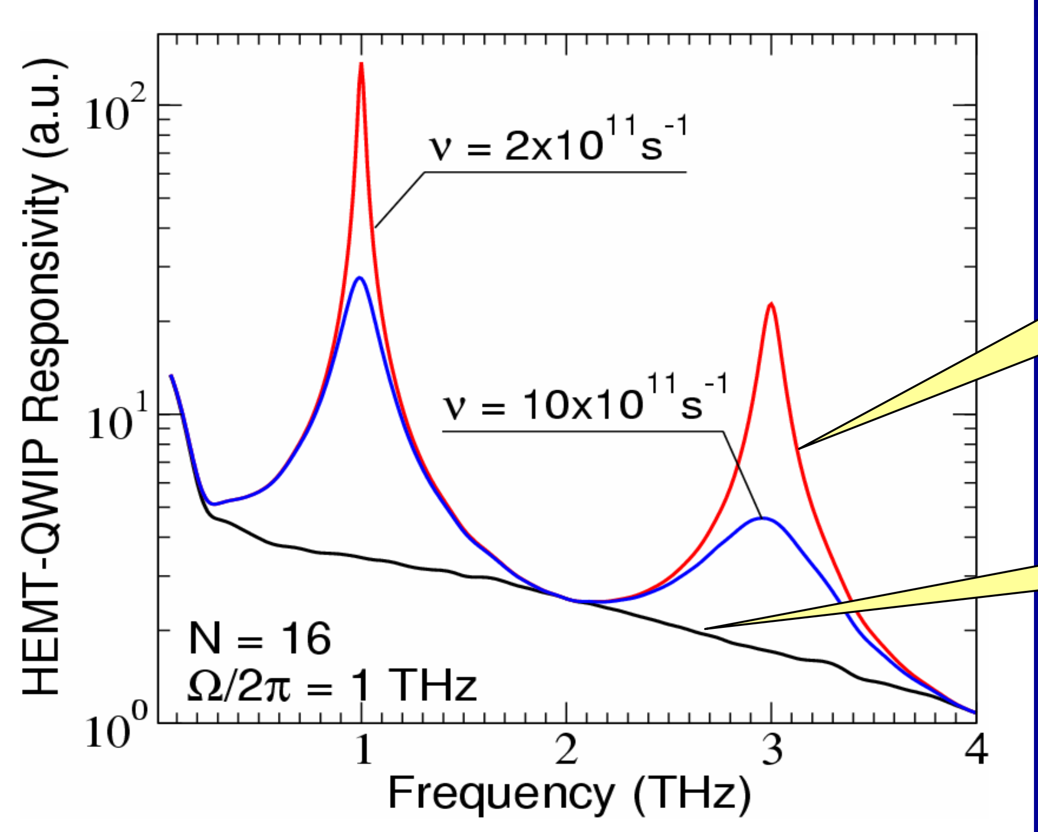


QWIP response (EMC particle modeling)



Long tales correspond to relatively strong QWIP response at THz frequencies – consequence of velocity overshoot of just photoexcited electrons

Responsivity of HEMT-QWIP photomixer



HEMT-QWIP response due to plasma resonances

QWIP response

Maximum THz power

$$P_{\mathrm{THz}} = r_a R^2 P_{\mathrm{Infra}}^2$$

$$\max|R| = \frac{\overline{R}(L_{os}/L_{\mathrm{QW}})}{(1+\Omega^2\tau_{os}^2)}\left(\frac{\Omega}{\nu}\right) \cong \overline{R}\left(\frac{L_{os}}{L_{\mathrm{QW}}}\right)\left(\frac{\Omega}{\nu}\right)$$

$$\max|P_{\mathrm{THz}}| = r_a\overline{R}^2\left(\frac{L_{os}}{L_{\mathrm{QW}}}\right)^2\left(\frac{\Omega}{\nu}\right)^2 P_{\mathrm{Infra}}^2$$

Estimate:

– incident infrared power P_{Infra} = 5 mW

– realistic parameters of HEMT, QWIP (at nitrogen temperatures), and antenna –

$\max|P_{\mathrm{THz}}|$ = 0.5 mW

r_a – radiation resistance of antenna,

R – HEMT-QWIP responsivity, P_{Infra} – power of infrared signal

Conclusions

- We have studied novel resonant terahertz photomixing and detector devices based on integration of a HEMT and QWIP structures.
- The devices have been assessed theoretically using the developed analytical and numerical models.
- HEMT-QWIP resonant photomixer can effectively transform infrared signals (radiation of two infrared lasers with close frequencies or ultrashort infrared pulses) into terahertz signals.