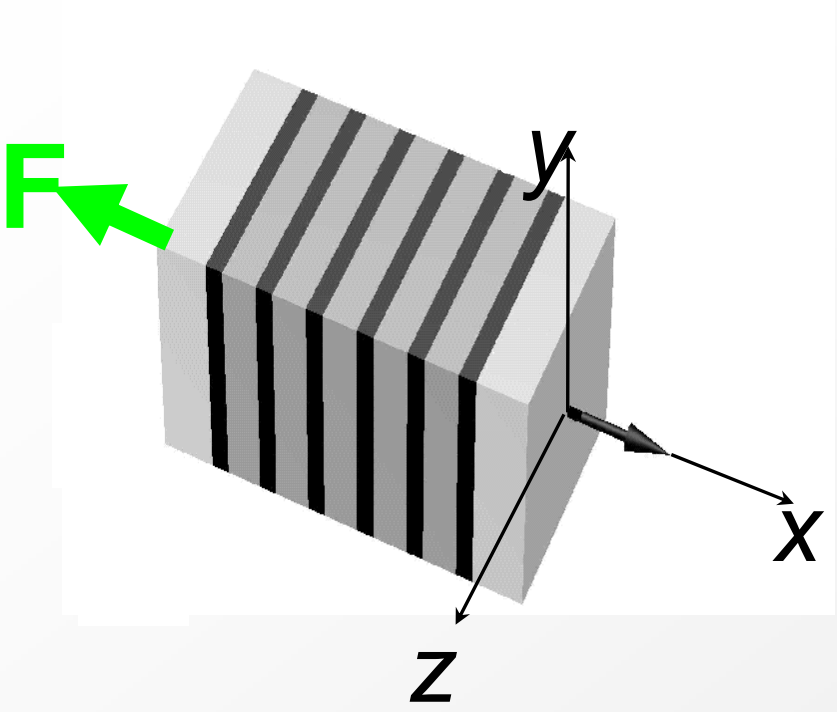

СИНХРОНИЗАЦИЯ СУБ-ТГЦ КОЛЕБАНИЙ В ПОЛУПРОВОДНИКОВОЙ СВЕРХРЕШЕТКЕ

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Collaborators

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A.E. Khramov (Saratov State University, Russia)
K.N. Alekseev (Loughborough University, UK)
M.T. Greenaway (University of Nottingham, UK)
T.M. Fromhold (University of Nottingham, UK)

Outlook

•Charge domain dynamics in semiconductor superlattice.

• Effect of magnetic field on charge domain motion

• Forced charge dynamics and synchronization phenomena induced by an external periodic signal

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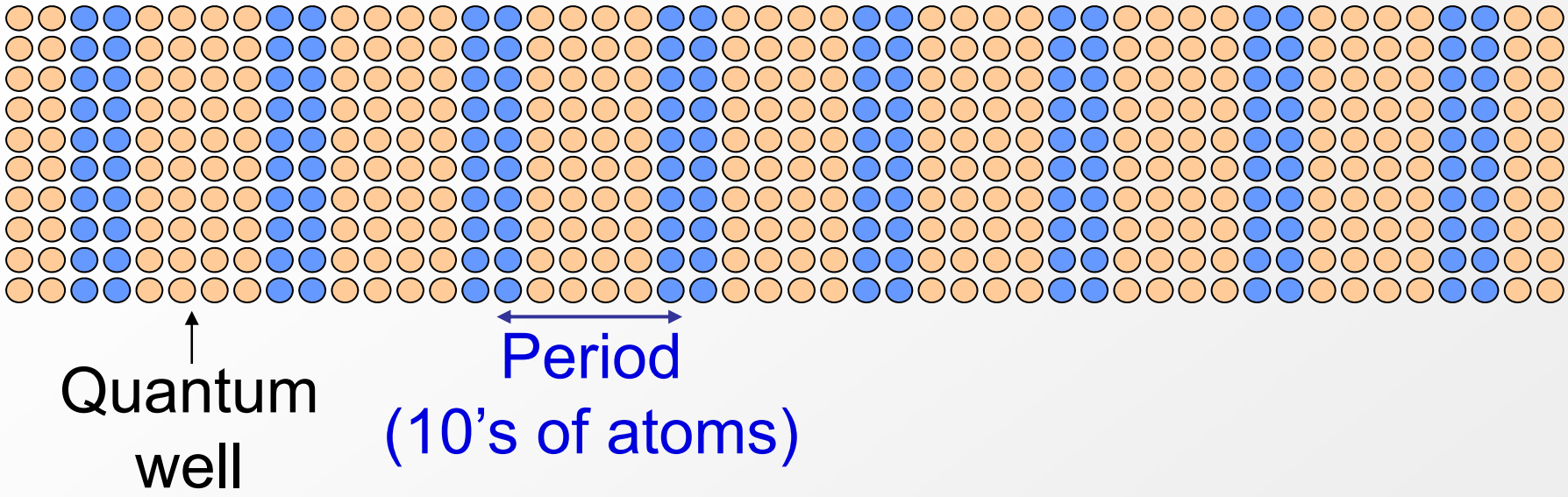
SEMICONDUCTOR SUPERLATTICE

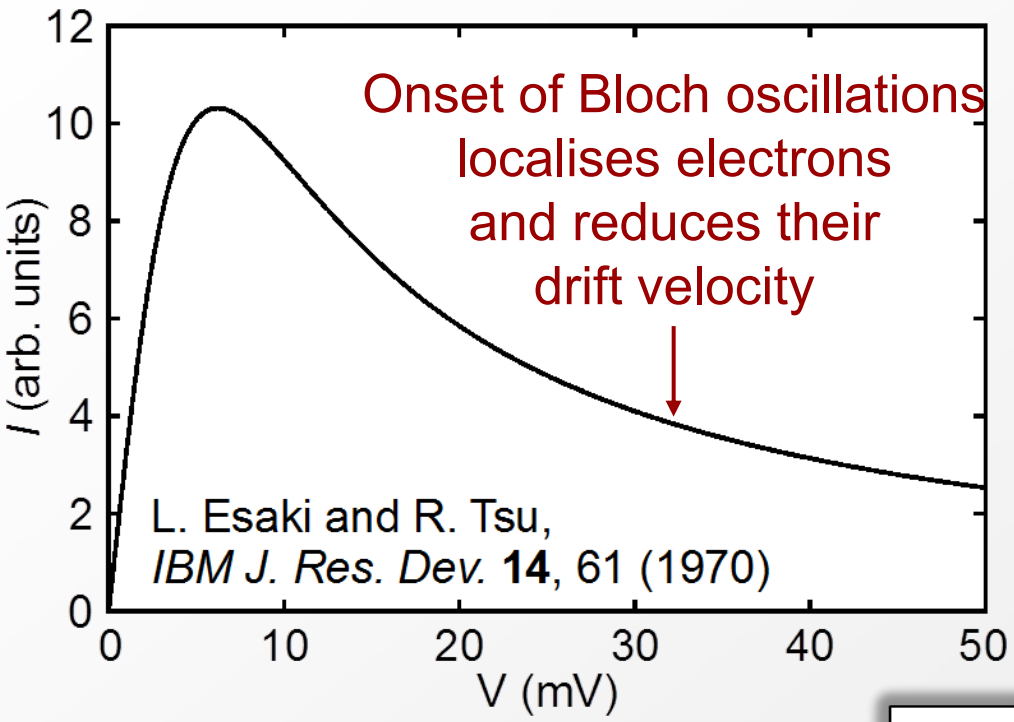


Chain of quantum wells forms a 1D periodic structure similar to a crystal lattice

But since the lattice period is much longer than for any natural crystal, this type of structure is known as a "Superlattice"

Drift velocity of electron, v_d

$I \sim v_d$



$$eF = \frac{dp_x}{dt}$$

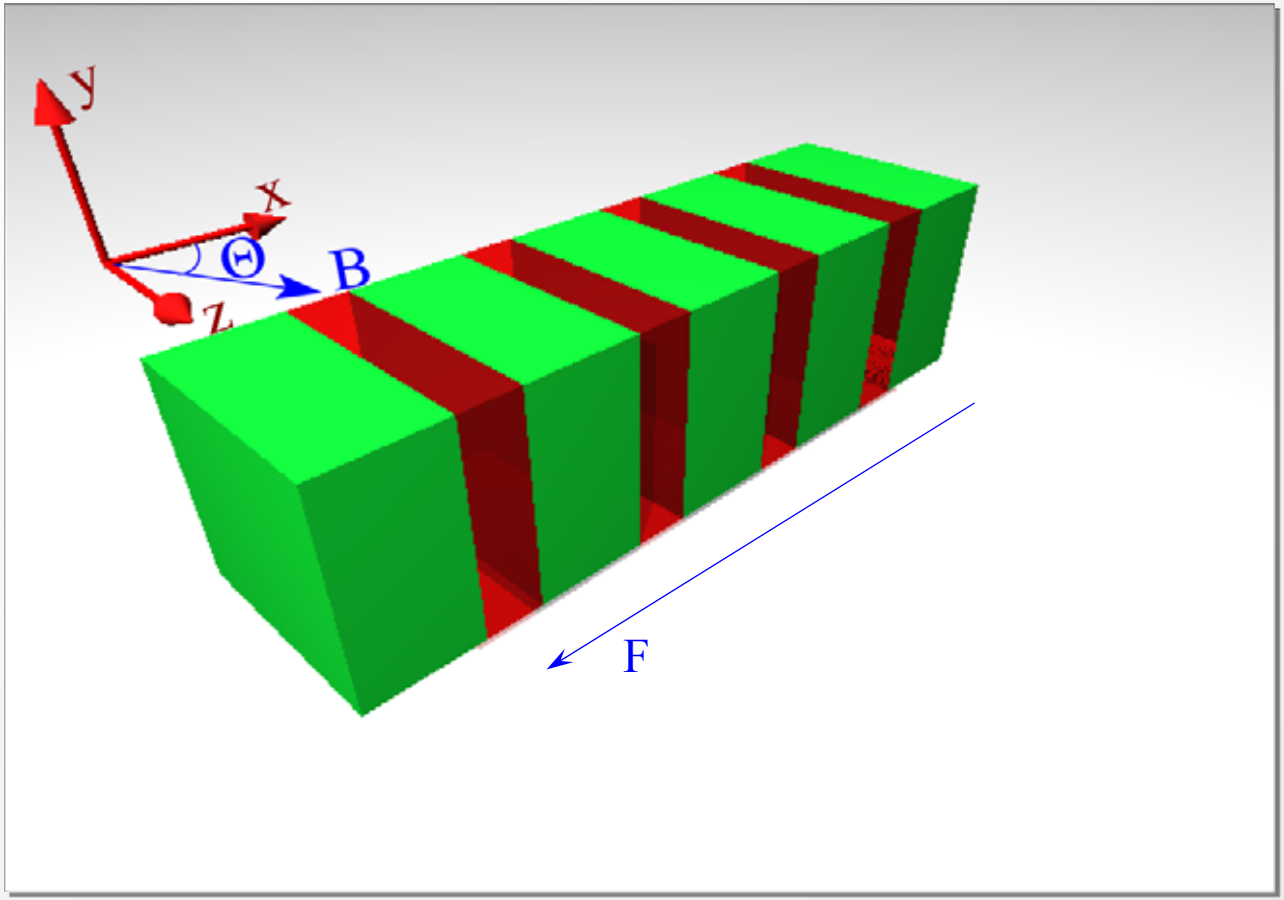
$$v_x = \frac{dE}{dp_x}$$

$$E(p_x) = \Delta(1 - \cos\frac{p_x d}{\hbar})$$

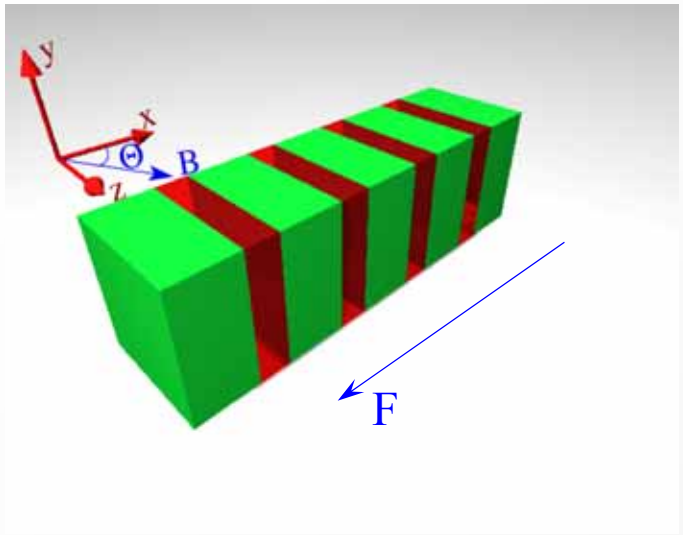
$$v_d(F) = \frac{1}{\tau}\sum\int_0^\infty v_x(t)\exp(-t/\tau)dt$$

How to control electron dynamics?

using magnetic field



MODEL EQUATIONS I:



Electric field: $\mathbf{F}(-F, 0, 0)$

Magnetic field: $\mathbf{B}(B\cos\Theta, 0, B\sin\Theta)$

Dispersion relation:

$$E(\mathbf{p}) = \frac{\Delta}{2}\left(1 - \cos\frac{p_x d}{\hbar}\right) + \frac{1}{2m^*}\left(p_y^2 + p_y^2\right)$$

Electron impulse: $\mathbf{p}(p_x, p_y, p_x)$

Balance equation: $\dot{\mathbf{p}} = -e\mathbf{F} - e(\nabla_{\mathbf{p}} E \times \mathbf{B})$

$$\dot{p}_x = eF - \omega_{\|} p_y \tan\Theta$$

$$\dot{p}_y = m^* \omega_{\|} \tan\Theta \frac{d\Delta}{2\hbar} \sin\left(\frac{p_x d}{\hbar}\right) - \omega_{\|} p_z$$

$$\dot{p}_z = \omega_{\|} p_y$$

Cyclotron frequency:

$$\omega_c = eB / m^*$$

$$\omega_{\|} = \omega_c \cos\Theta$$

MODEL EQUATIONS II:

$$\ddot{p}_z + \omega_{\parallel}^{\ 2} p_z = -\frac{m^* \omega_c^2 \Delta \sin 2\Theta}{4\hbar} \sin\left(\frac{d \tan\Theta}{\hbar} p_z - \omega_b t\right)$$

All other states can be expressed in terms of p_z:

$$p_x = eFt - \dot{p}_z \tan\Theta, \quad p_y = \omega_{\parallel}^{-1} \dot{p}_z$$

$$\dot{x} = \frac{d\Delta}{2\hbar} \sin\left(\frac{d \tan\Theta}{\hbar} p_z - \omega_b t\right), \quad \dot{y} = \frac{\dot{p}_z}{\omega_{\parallel} m^*}, \quad \dot{z} = \frac{\dot{p}_z}{m^*}$$

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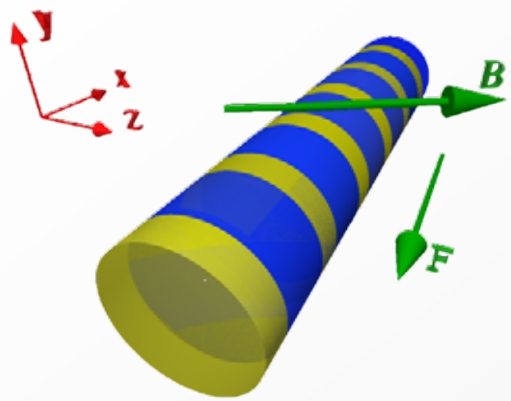
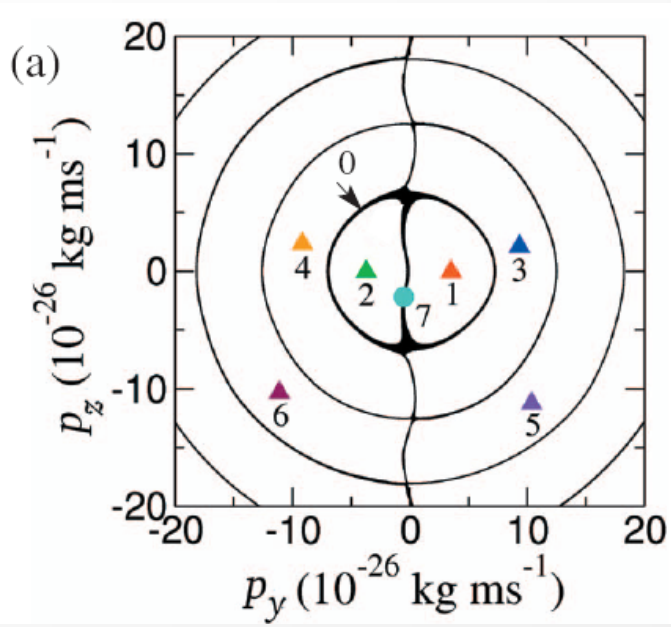
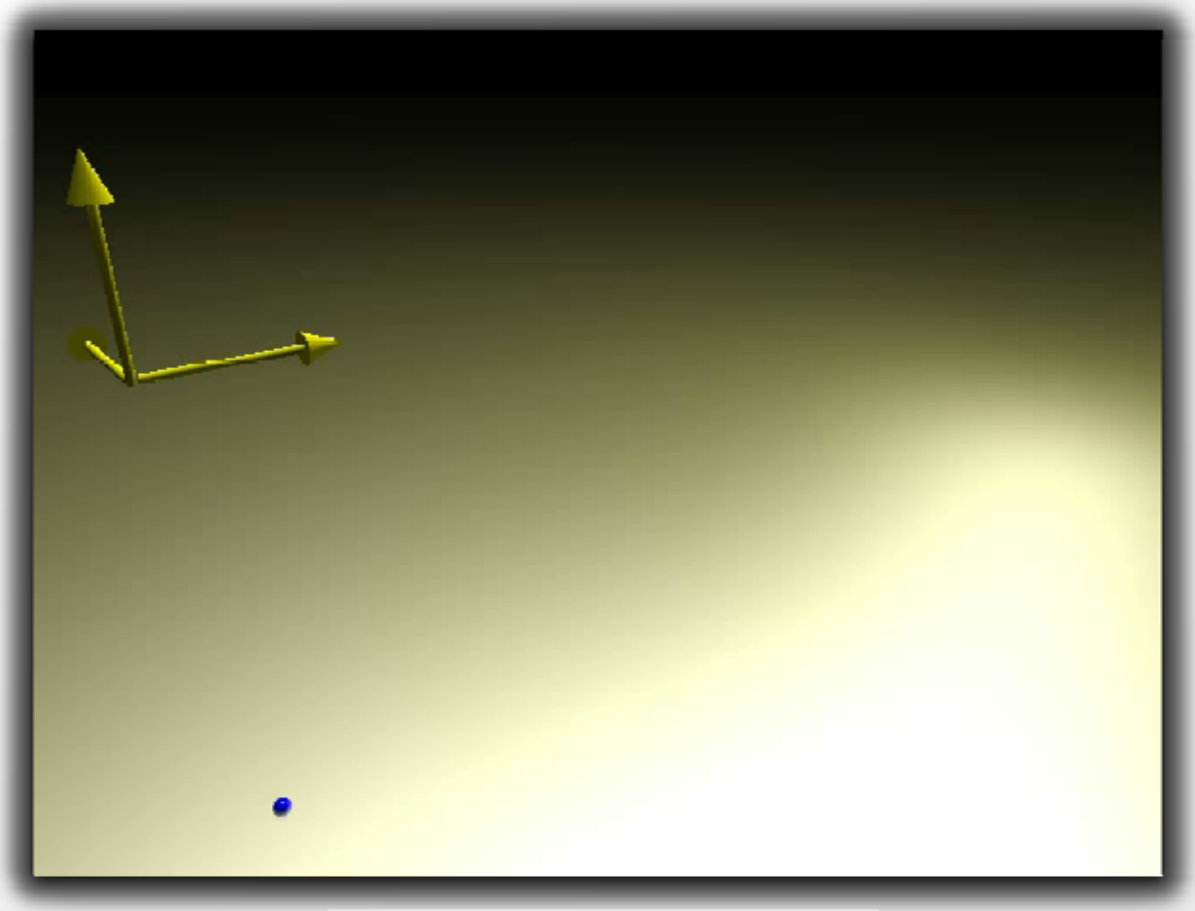
Chaotic electron's trajectory at cyclotron-Bloch resonance





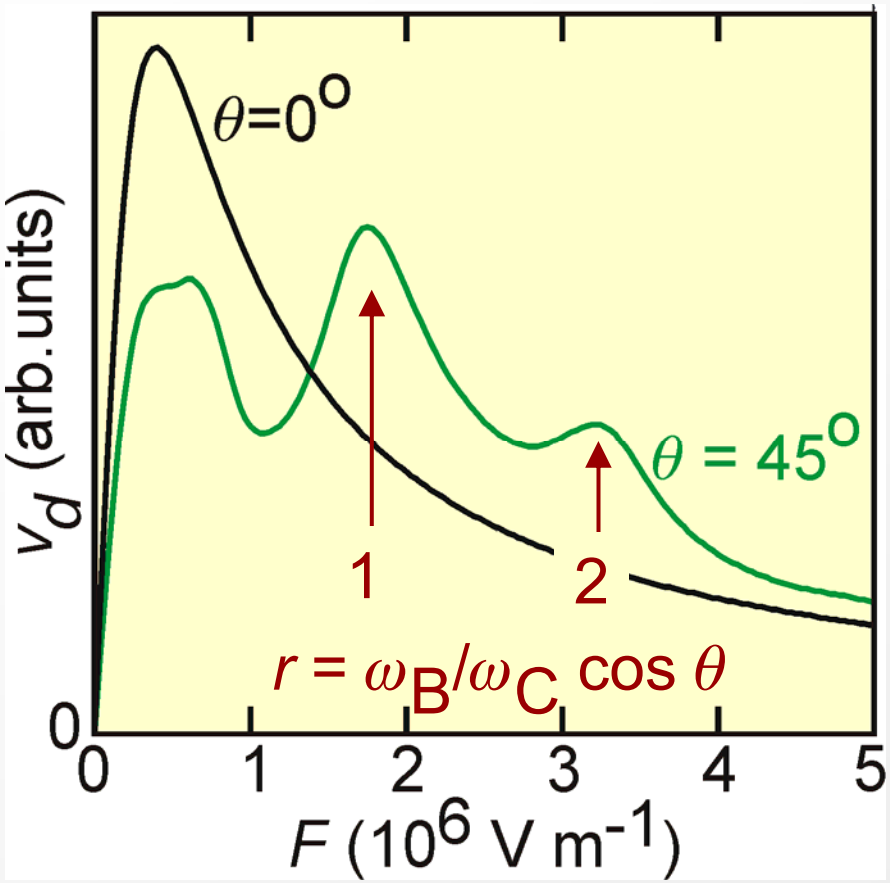


$$\omega_b / \omega_c \cos\Theta = 1$$

ELECTRON DRIFT VELOCITY

175 fs

$$v_d(F) = \frac{1}{\tau}\sum\int_0^\infty v_x(t)\exp(-t/\tau)dt$$



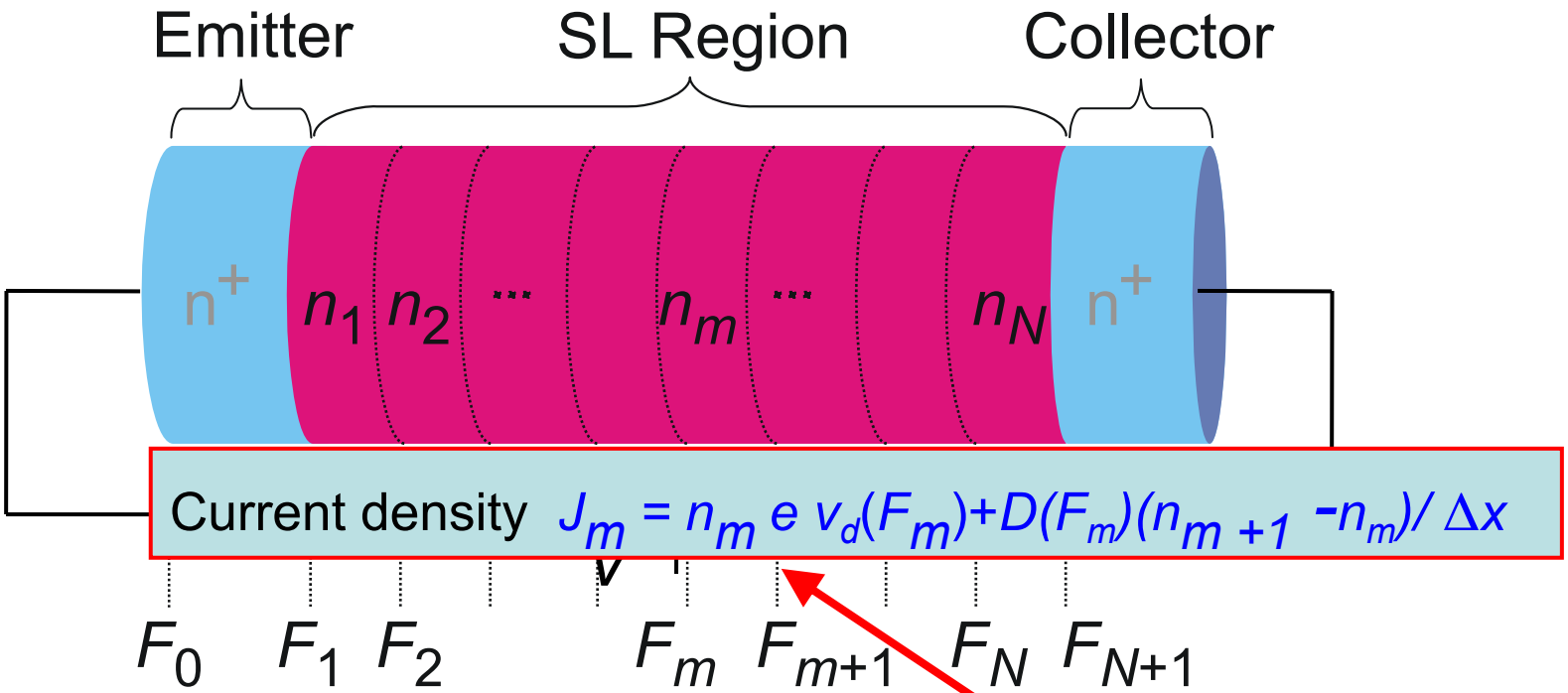
$v_d(F)$ curves were used as a basis for calculating $I(V)$

by self-consistent solution of

- Current continuity equation
- Poisson's equation

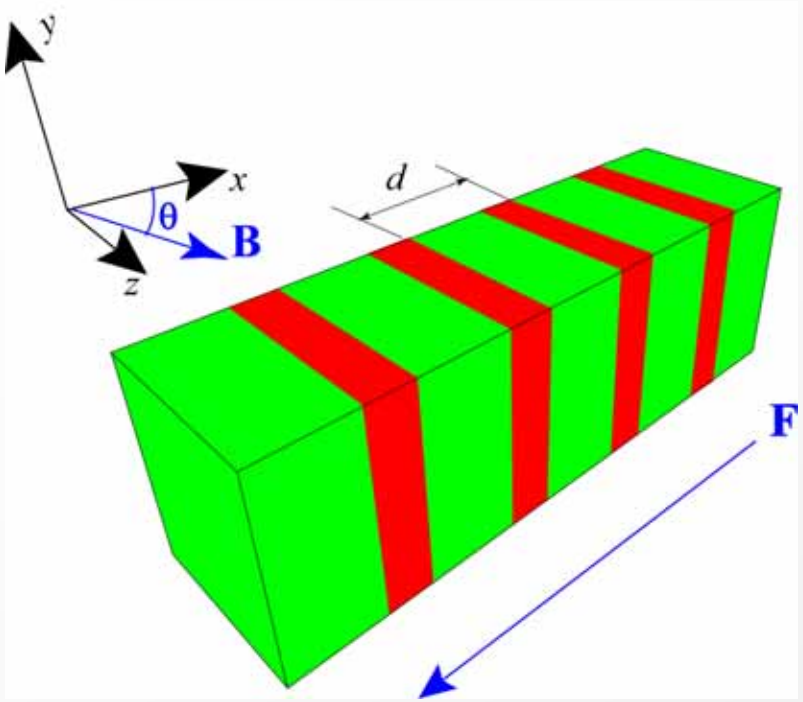
throughout the device

Semiclassical transport model



- Solve charge conservation equations $dn_m/dt = (J_m - J_{m+1})/e\Delta x$,
- and Poisson equations $F_{m+1} - F_m = (n_m - n_D)\, e\Delta x / \varepsilon_0 \varepsilon_r$
- self-consistently requiring sum of voltage drops = V
- Calculate current $I(t) = \frac{A}{N+1} \sum_{m=0}^{N} J_m$

Полупроводниковая сверхрешетка



Параметры сверхрешетки

d = 8.3 нм – период сверхрешетки

$m^* = 0.067 m_e$ – эффективная масса

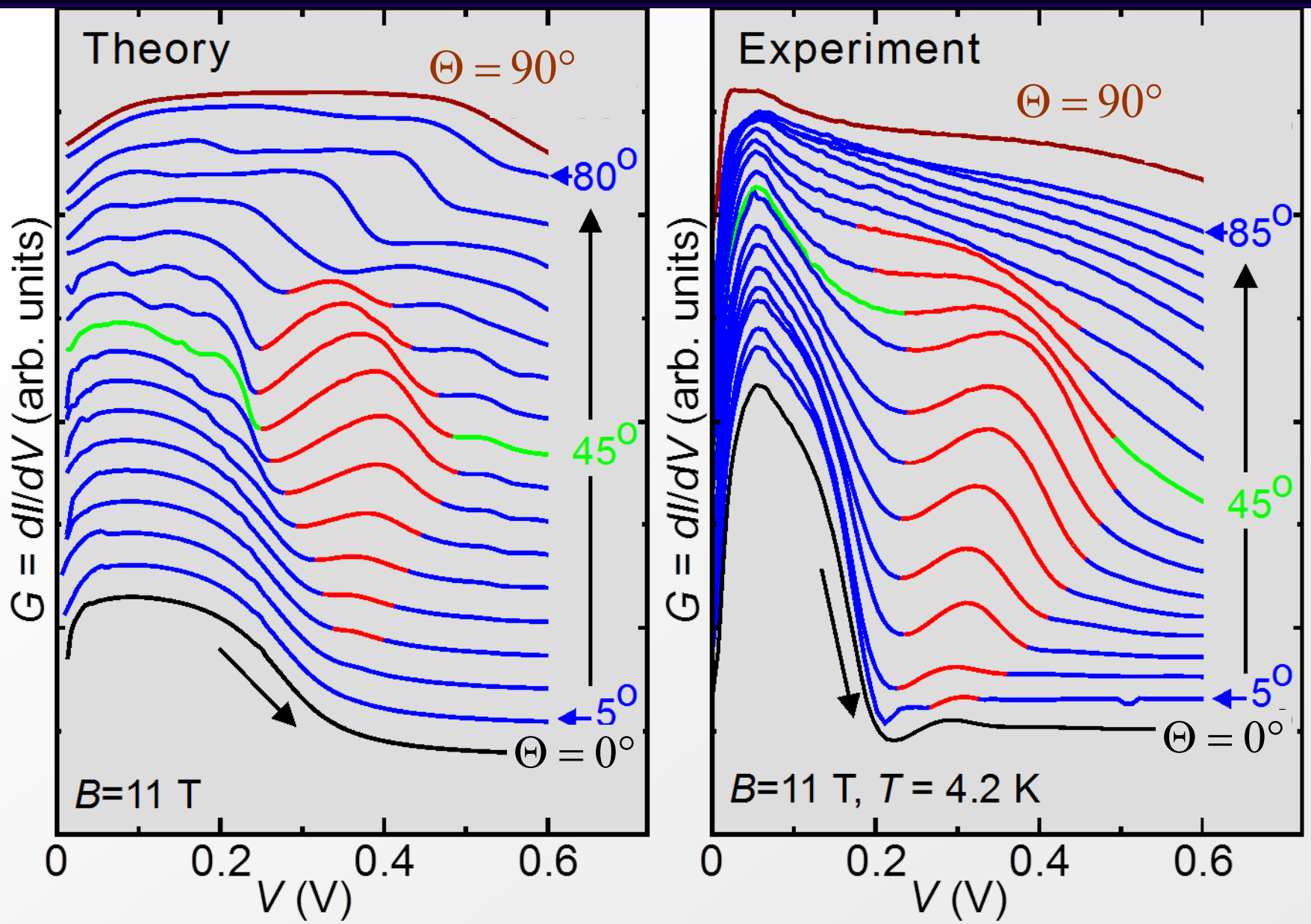
Δ_0= 19.1 мэВ – ширина минизоны

$A = 5\times10^{-10}$ м^2 – площадь сечения

L = 115.2 нм – длина сверхрешетки

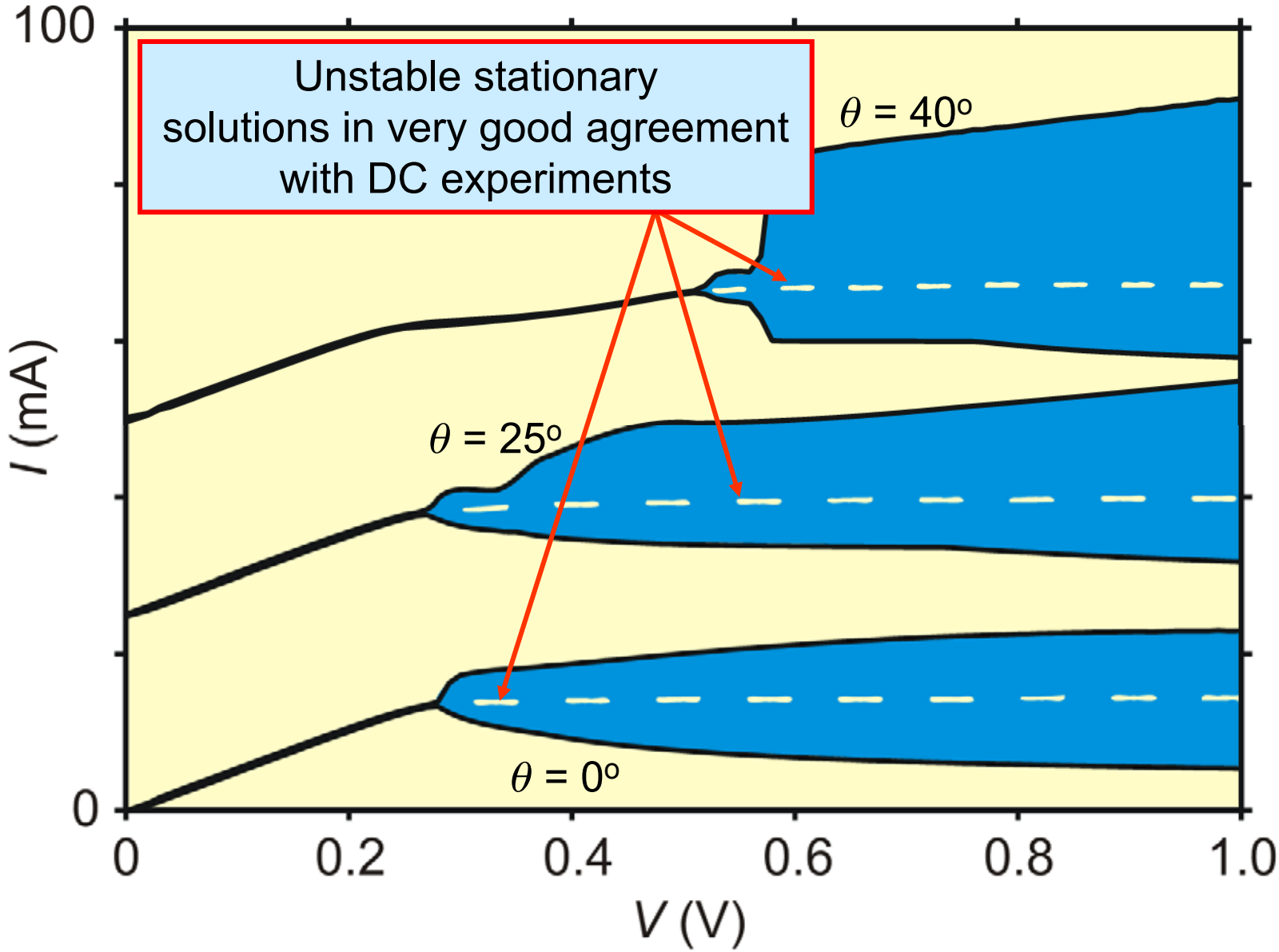
L_c = 50 нм – длина контакта

Fromhold T. M. et al. Chaotic electron diffusion through stochastic webs enhances current flow in superlattices. Nature. **428** (2004) 726-730



Fromhold et al, *Nature* **428,** 726 (2004)

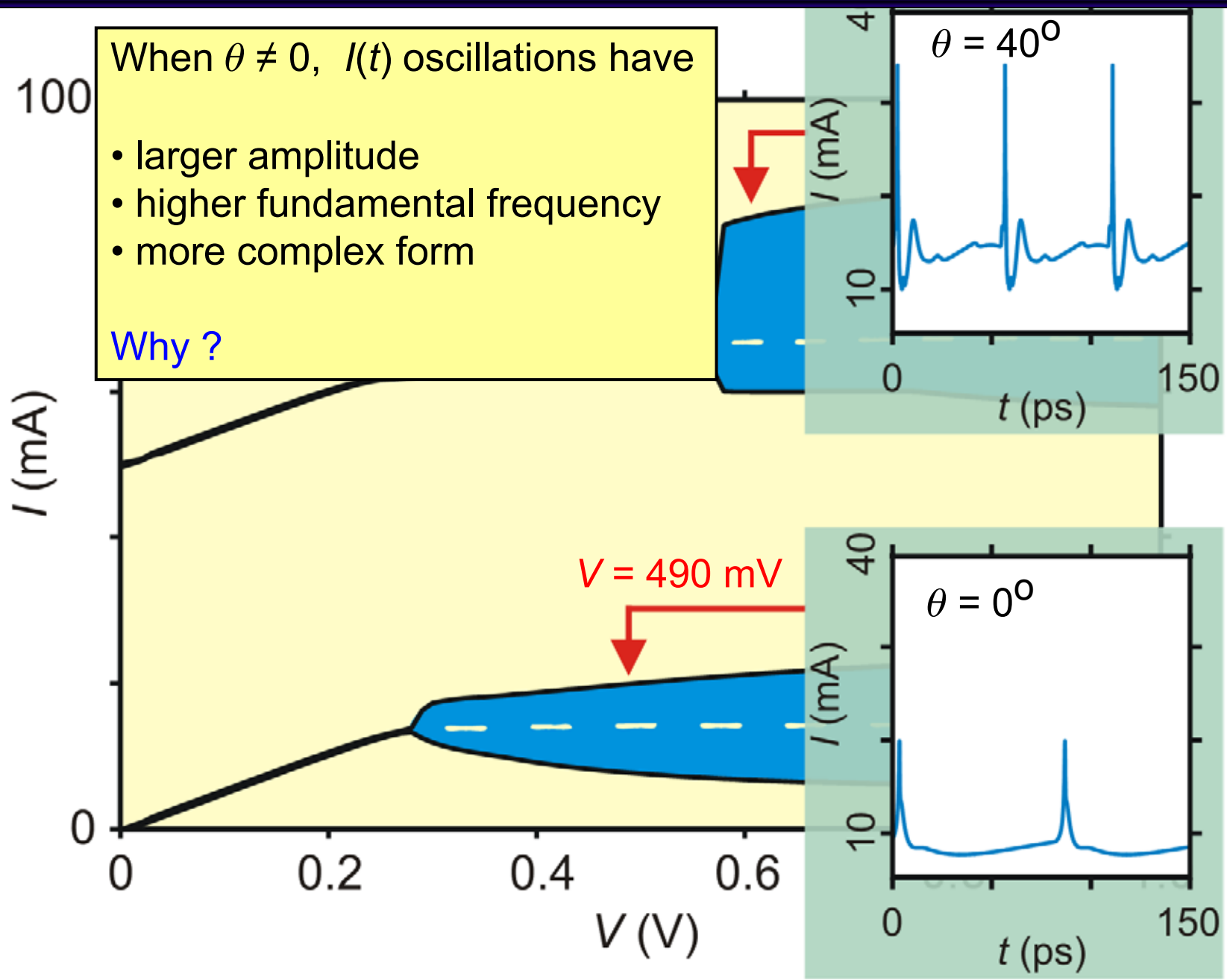
Theory

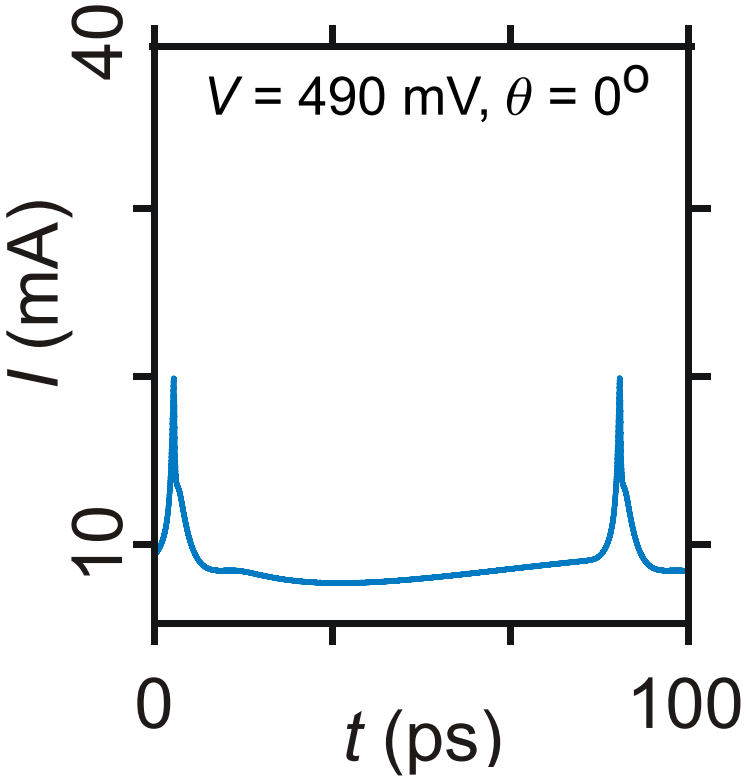

Unstable stationary solutions in very good agreement with DC experiments
θ = 40°
θ = 25°
θ = 0°
100
0
I (mA)
0
0.2
0.4
0.6
0.8
1.0
V (V)

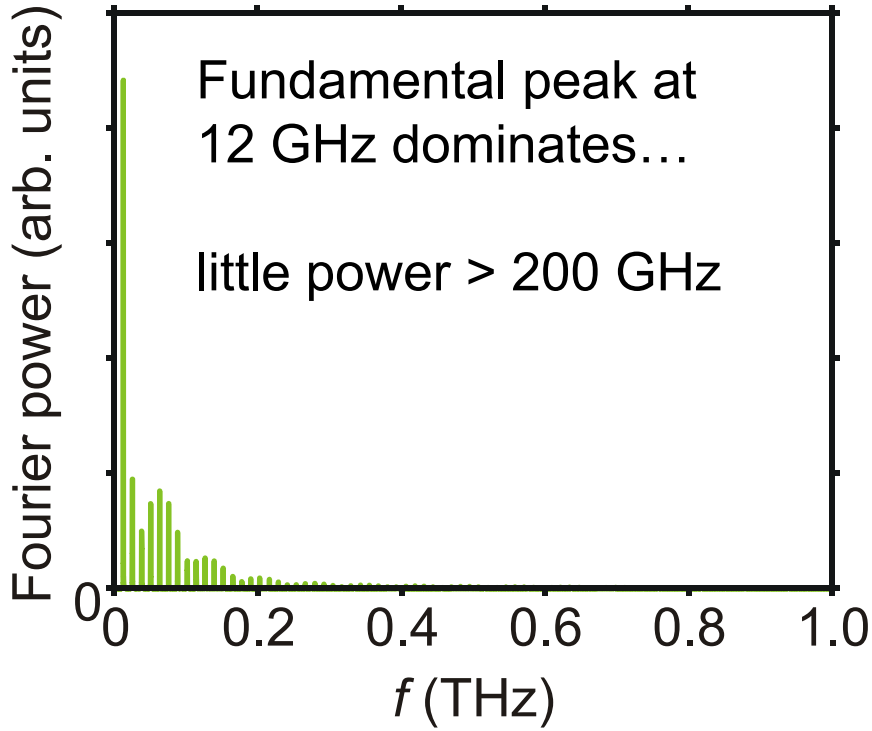
When $\theta \neq 0$, $I(t)$ oscillations have

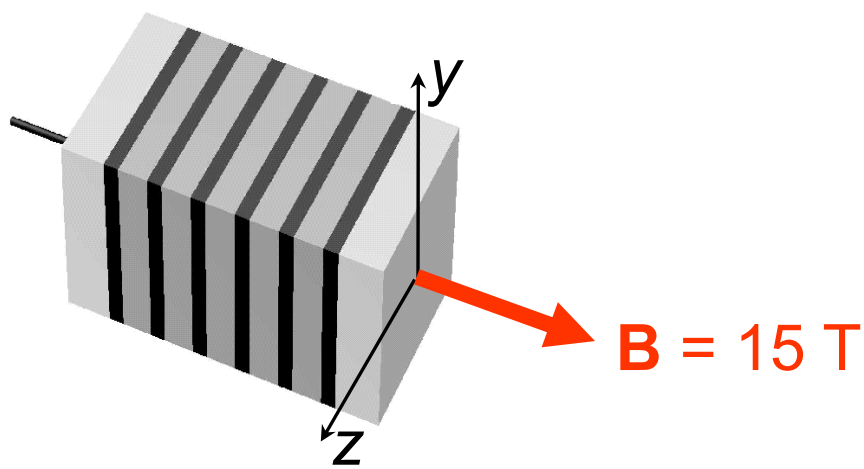
- larger amplitude
- higher fundamental frequency
- more complex form

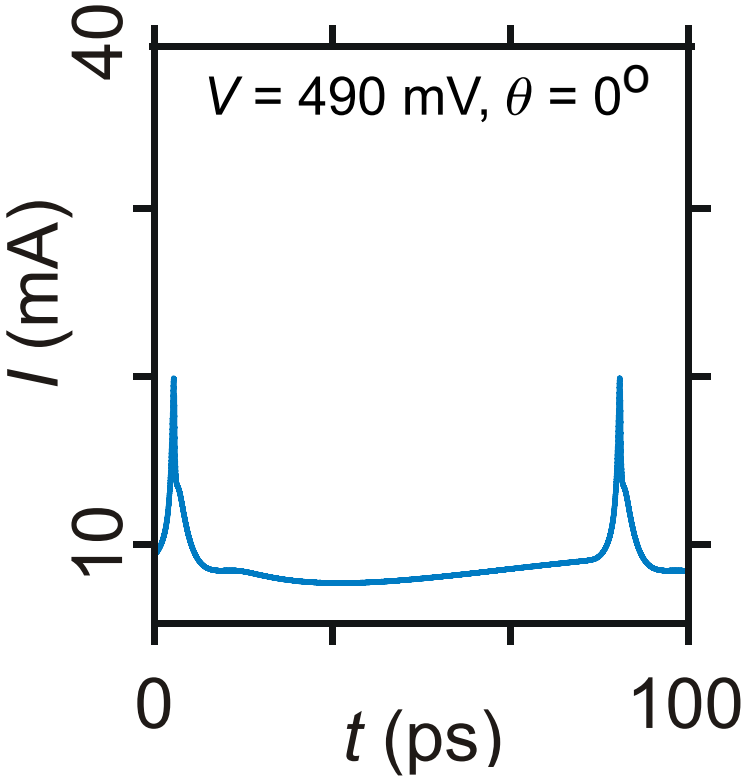
Why ?

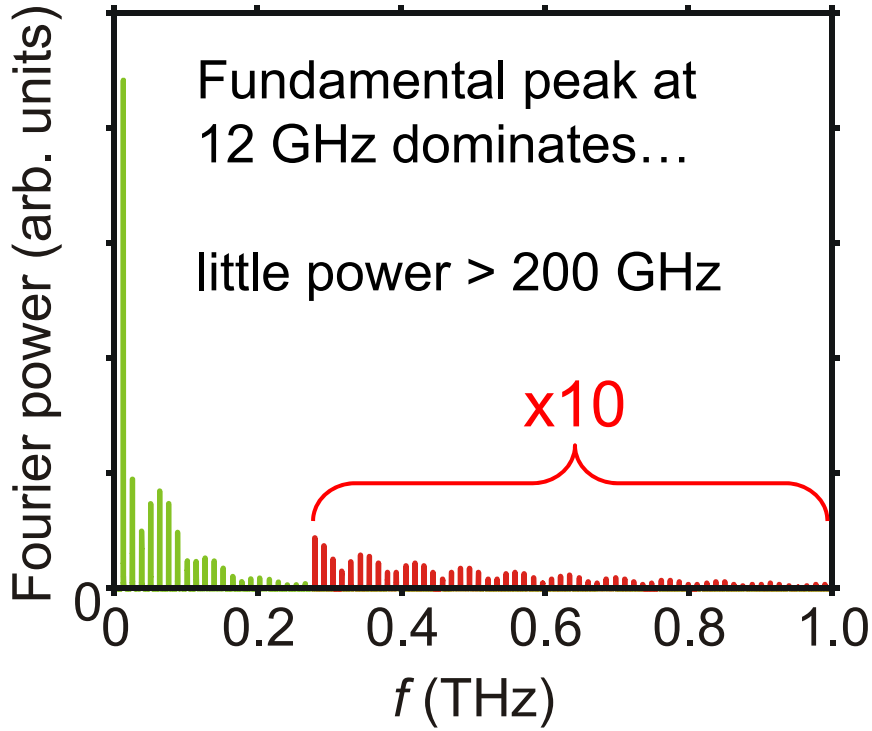


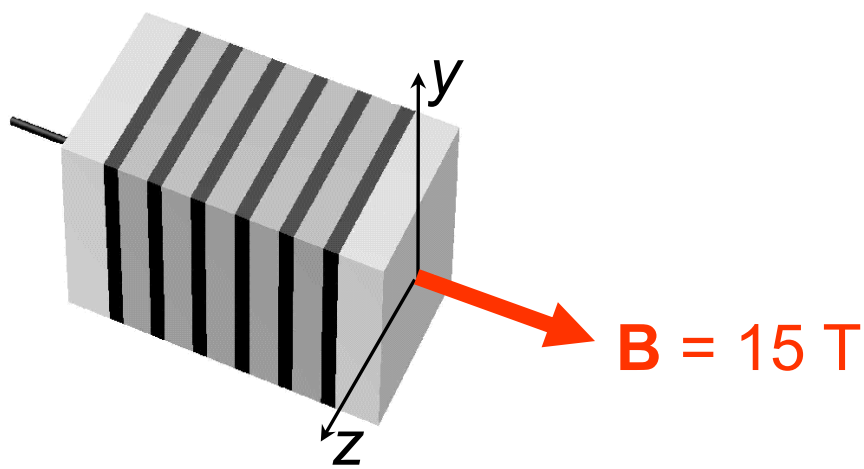

V = 490 mV, θ = 0°
I (mA)
40
10
0
100
t (ps)

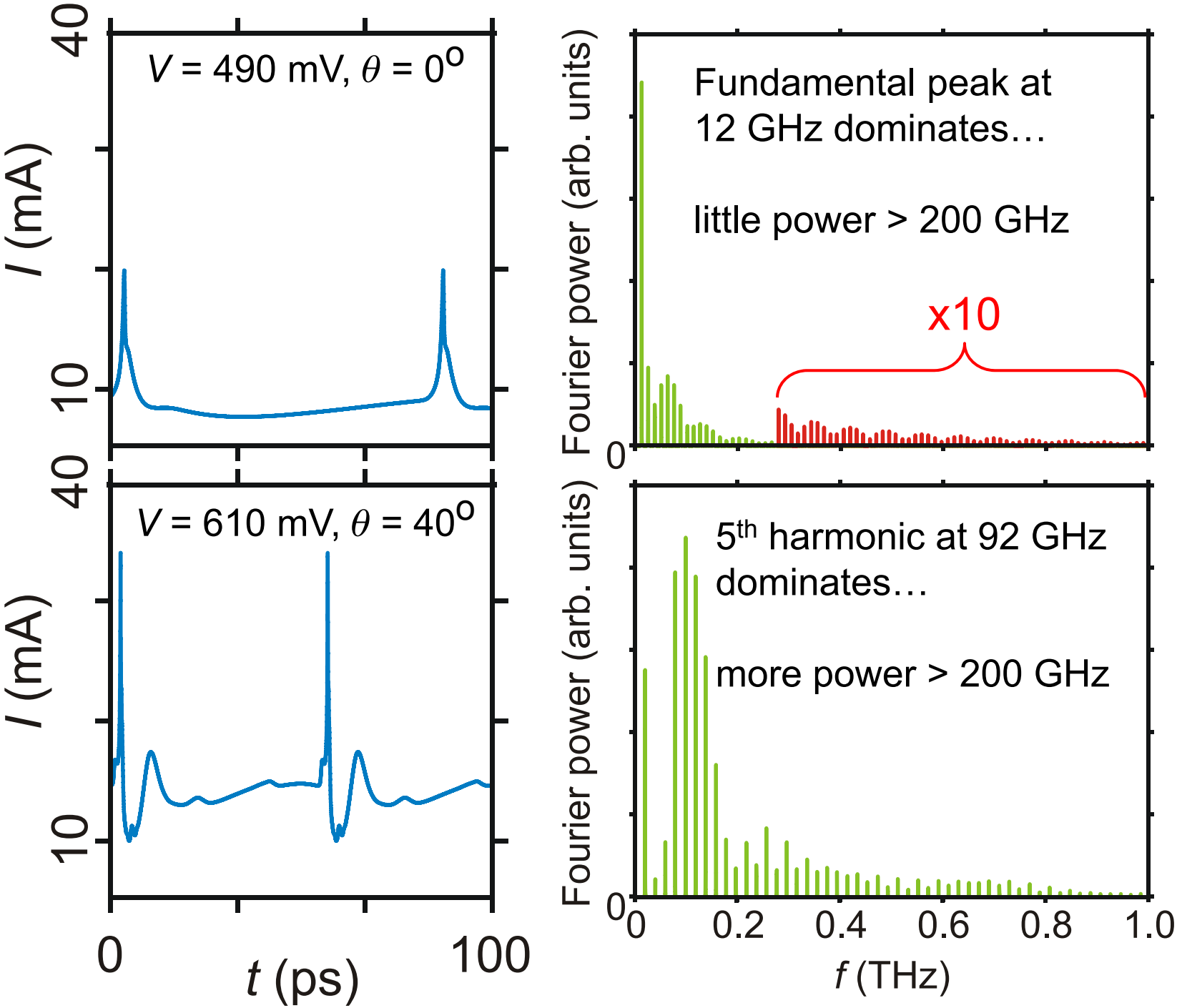

Fundamental peak at
12 GHz dominates…
little power > 200 GHz
Fourier power (arb. units)
0
0.2
0.4
0.6
0.8
1.0
f (THz)

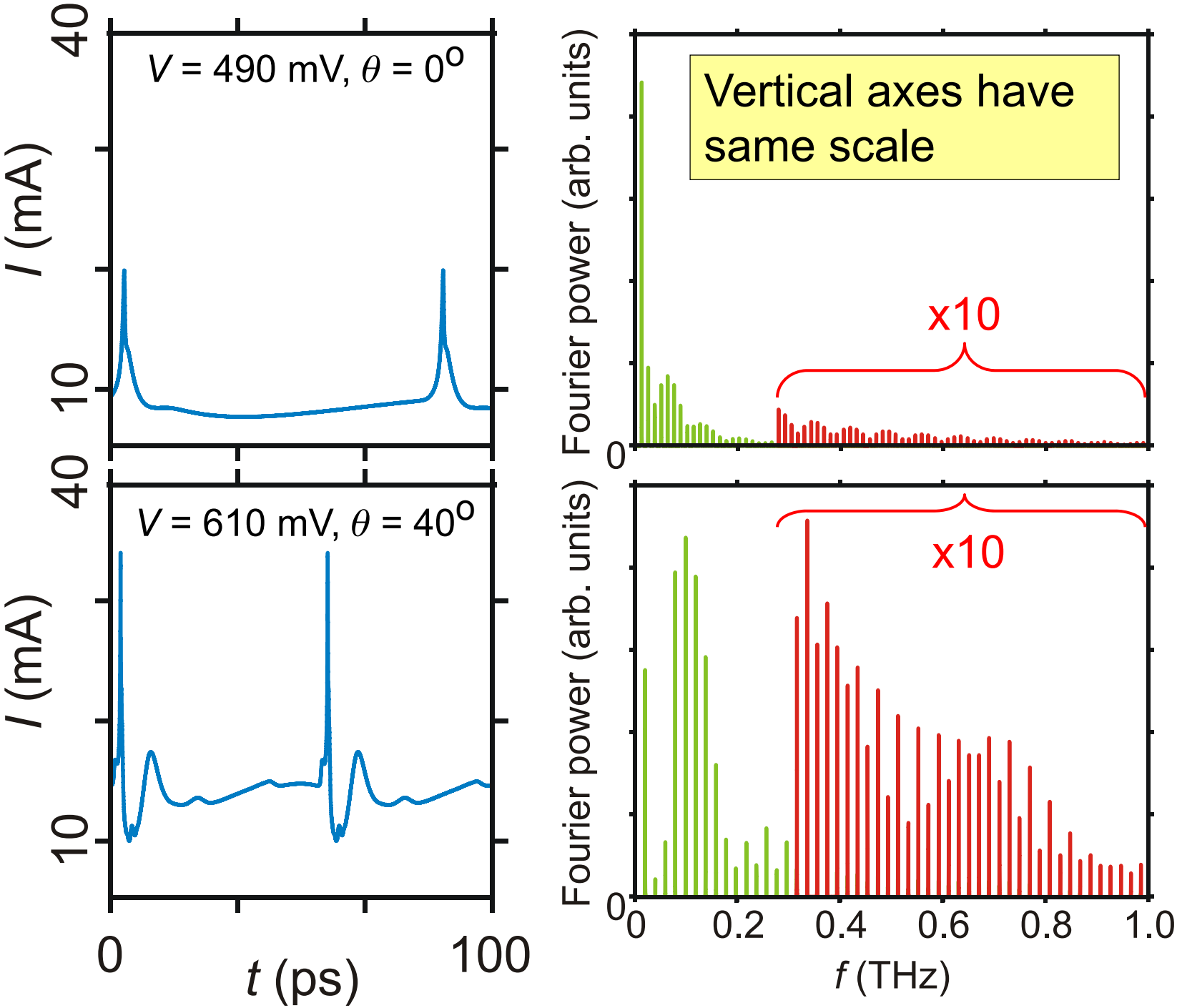

y
z
B = 15 T


V = 490 mV, θ = 0°
I (mA)
40
10
0
100
t (ps)

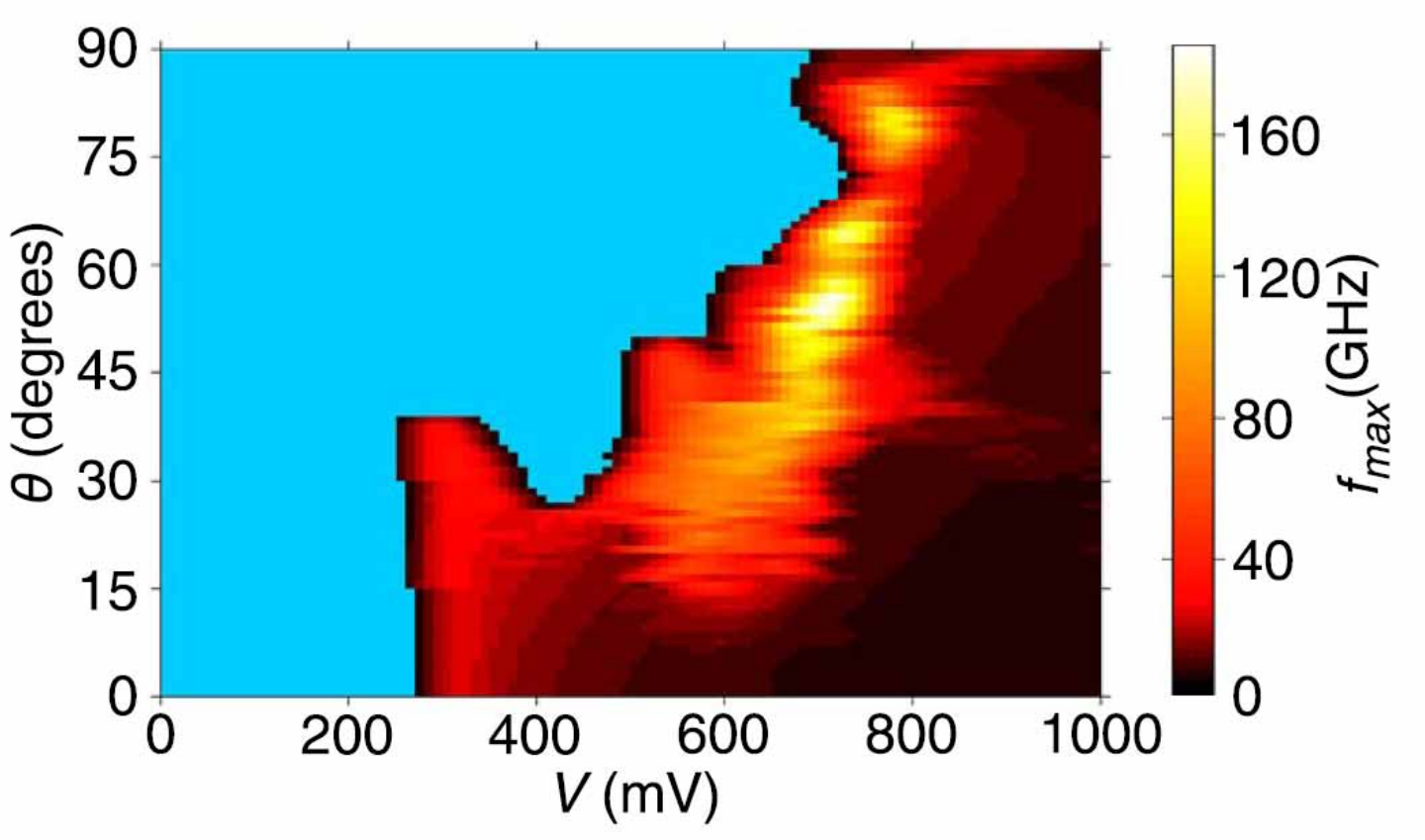

Fundamental peak at
12 GHz dominates…
little power > 200 GHz
x10
Fourier power (arb. units)
0
0.2
0.4
0.6
0.8
1.0
f (THz)


y
z
B = 15 T


V = 490 mV, θ = 0°
V = 610 mV, θ = 40°
I (mA)
40
10
0
100
t (ps)
Fundamental peak at
12 GHz dominates…
little power > 200 GHz
x10
5th harmonic at 92 GHz
dominates…
more power > 200 GHz
Fourier power (arb. units)
0
0.2
0.4
0.6
0.8
1.0
f (THz)

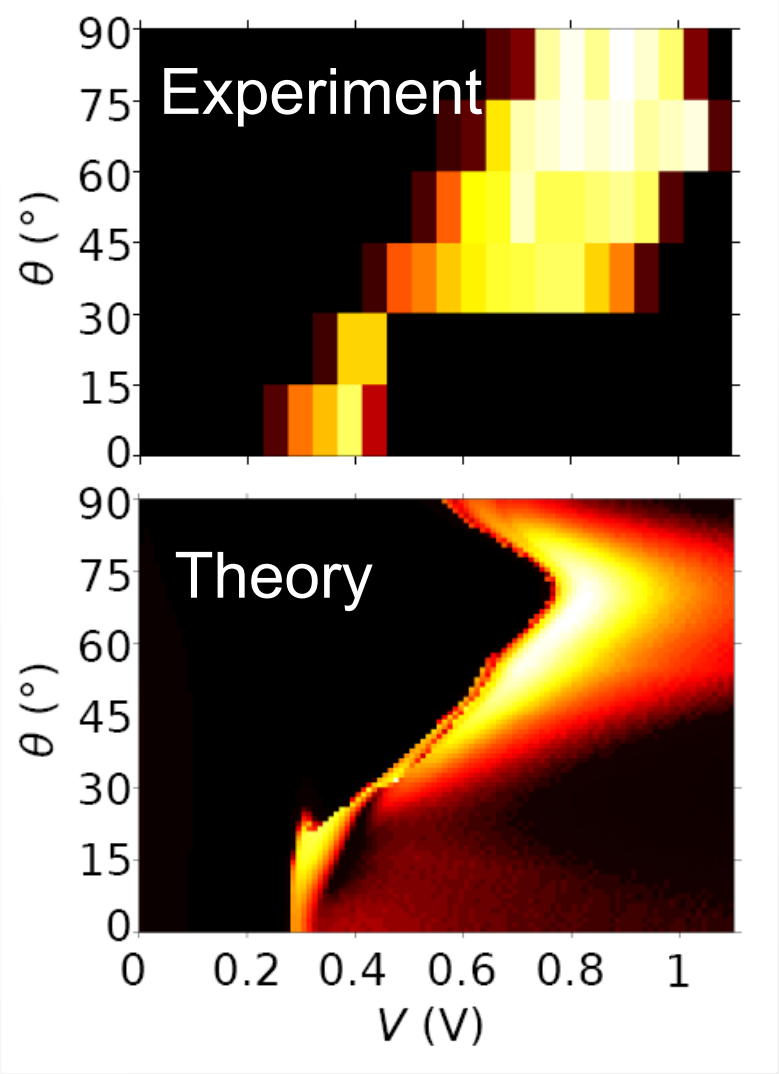

V = 490 mV, θ = 0°
V = 610 mV, θ = 40°
I (mA)
40
10
0
100
t (ps)
Vertical axes have same scale
x10
Fourier power (arb. units)
0
0.2
0.4
0.6
0.8
1.0
f (THz)

Frequency of the largest peak in the spectrum of current oscillations

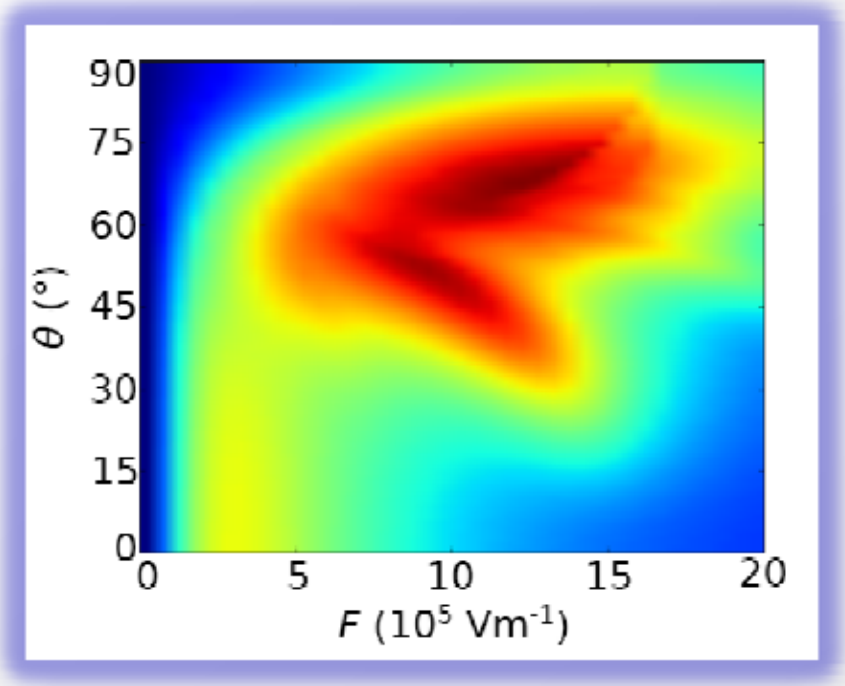


M. Greenaway et al, PRB 80 205308 (2009)

Total power of current oscillations

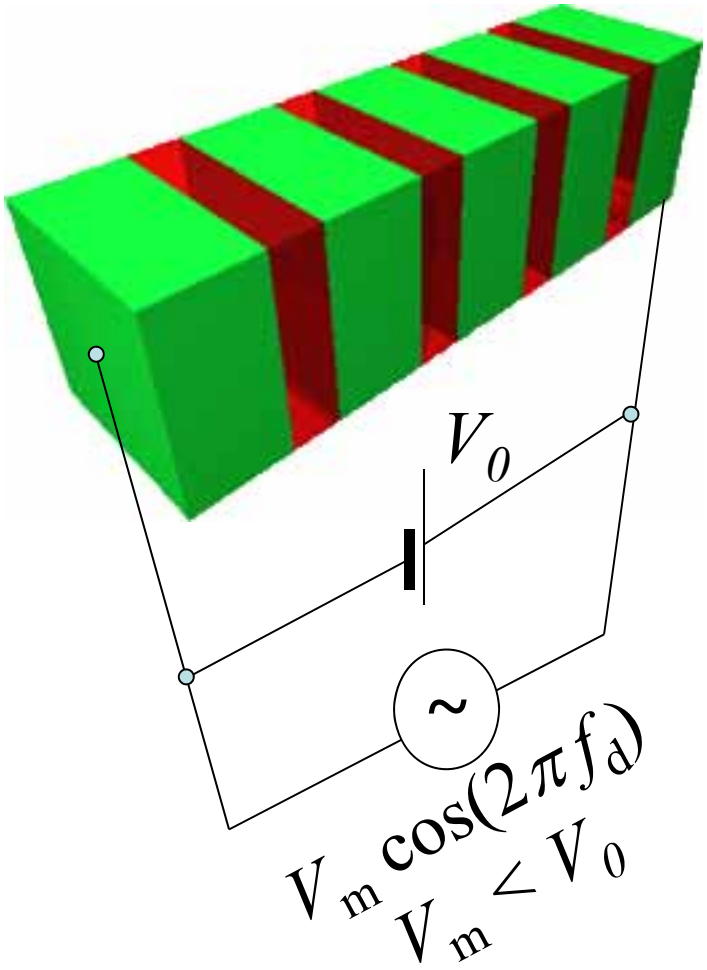


drift velocity (theory)



N. Alexeeva et al, 2011

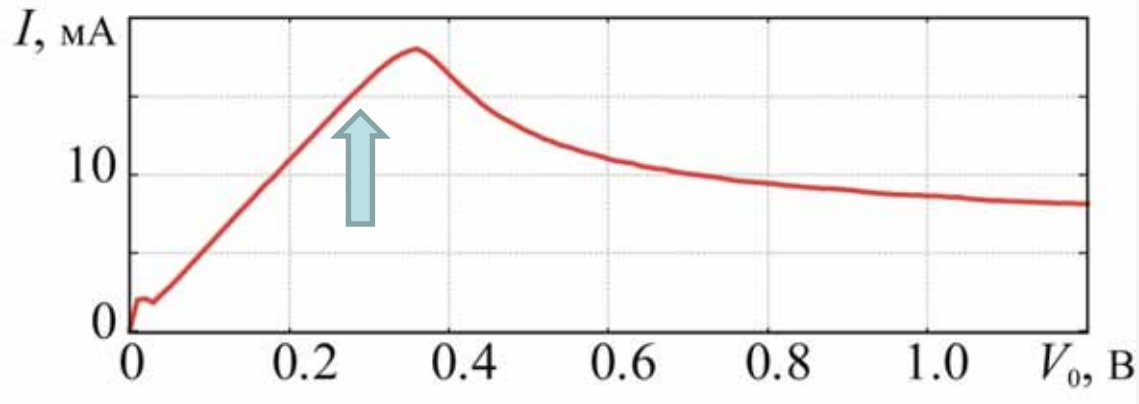
Полупроводниковая сверхрешетка под внешним периодическим воздействием



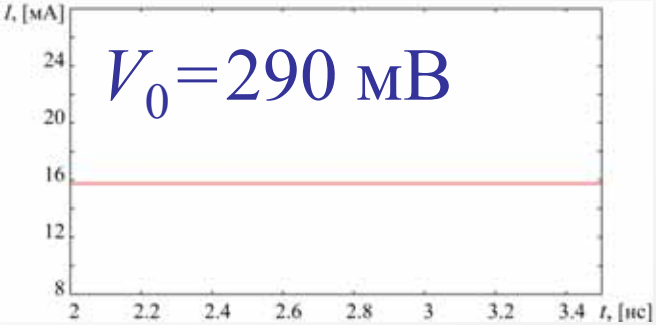
S.A. Ktitorov et al, Sov. Phys. Solid State 13, 1872 (1971)

T. Hyart et al, PRB 77, 165330 (2008)

Вольтамперные характеристики (ВАХи)



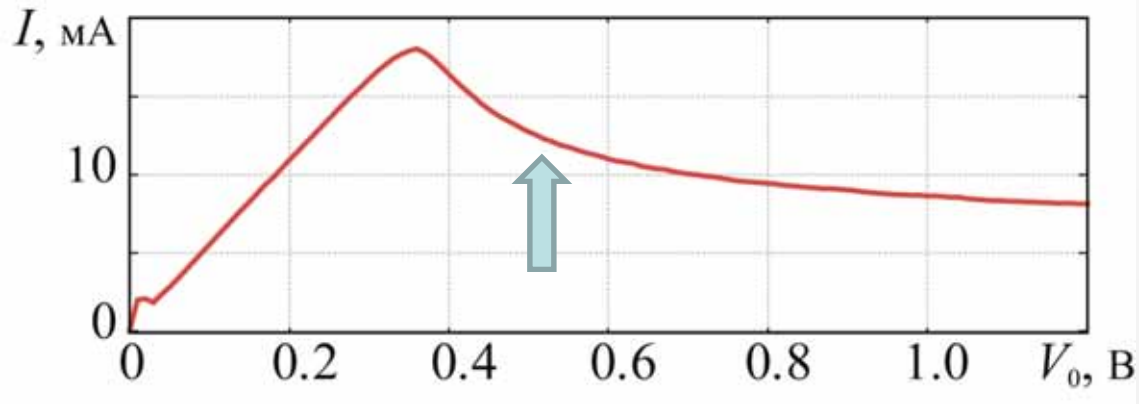
$V_m = 0$



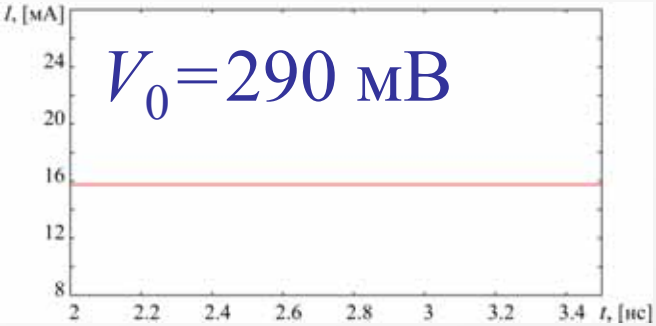
$V_0 = 290$ мВ

Esaki L., Tsu R. Superlattices and Negative Differential Conductivity in Semiconductors. IBM Journal of Research and Development. **14** (1) (1970) 61-65

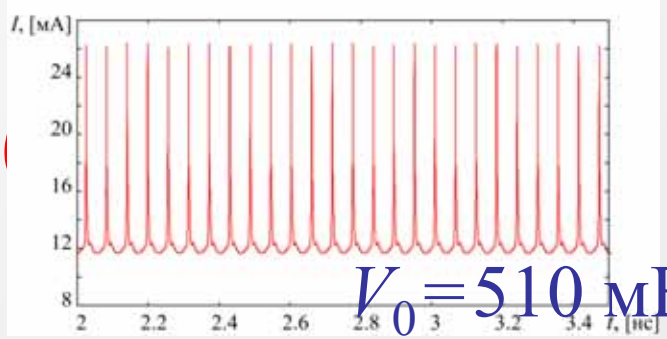
Вольтамперные характеристики (ВАХи)



$V_m = 0$



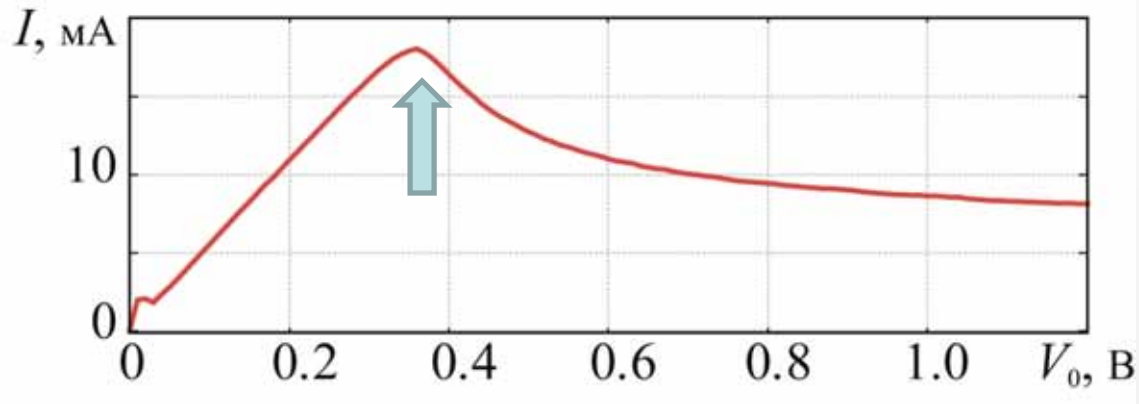
$V_0 = 290$ мВ



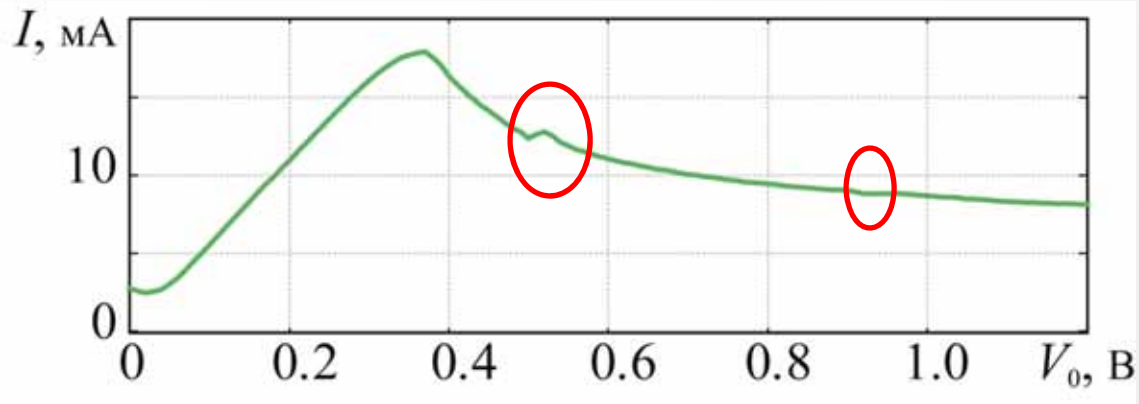
$V_0 = 510$ мВ

Esaki L., Tsu R. Superlattices and Negative Differential Conductivity in Semiconductors. IBM Journal of Research and Development. **14** (1) (1970) 61-65

Вольтамперные характеристики (ВАХи)



$V_m = 0$

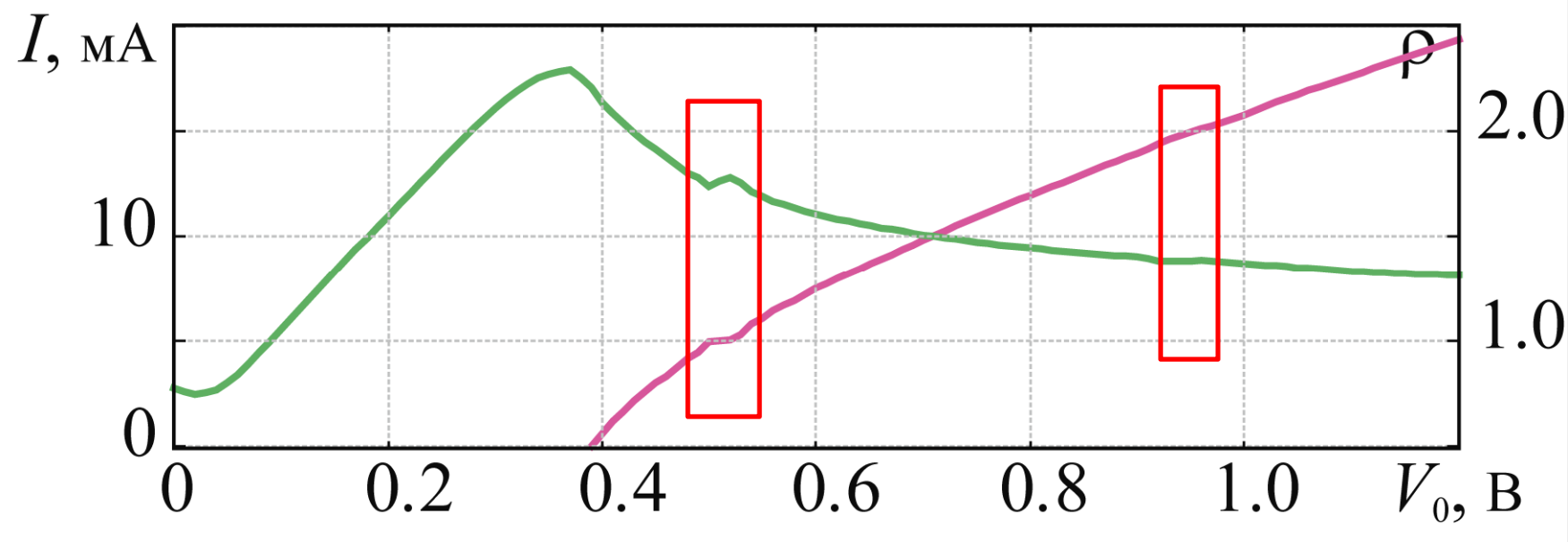


$V_m = 30$ мВ, $f_e = 17.3$ ГГц

Синхронизация колебаний заряда внешним воздействием

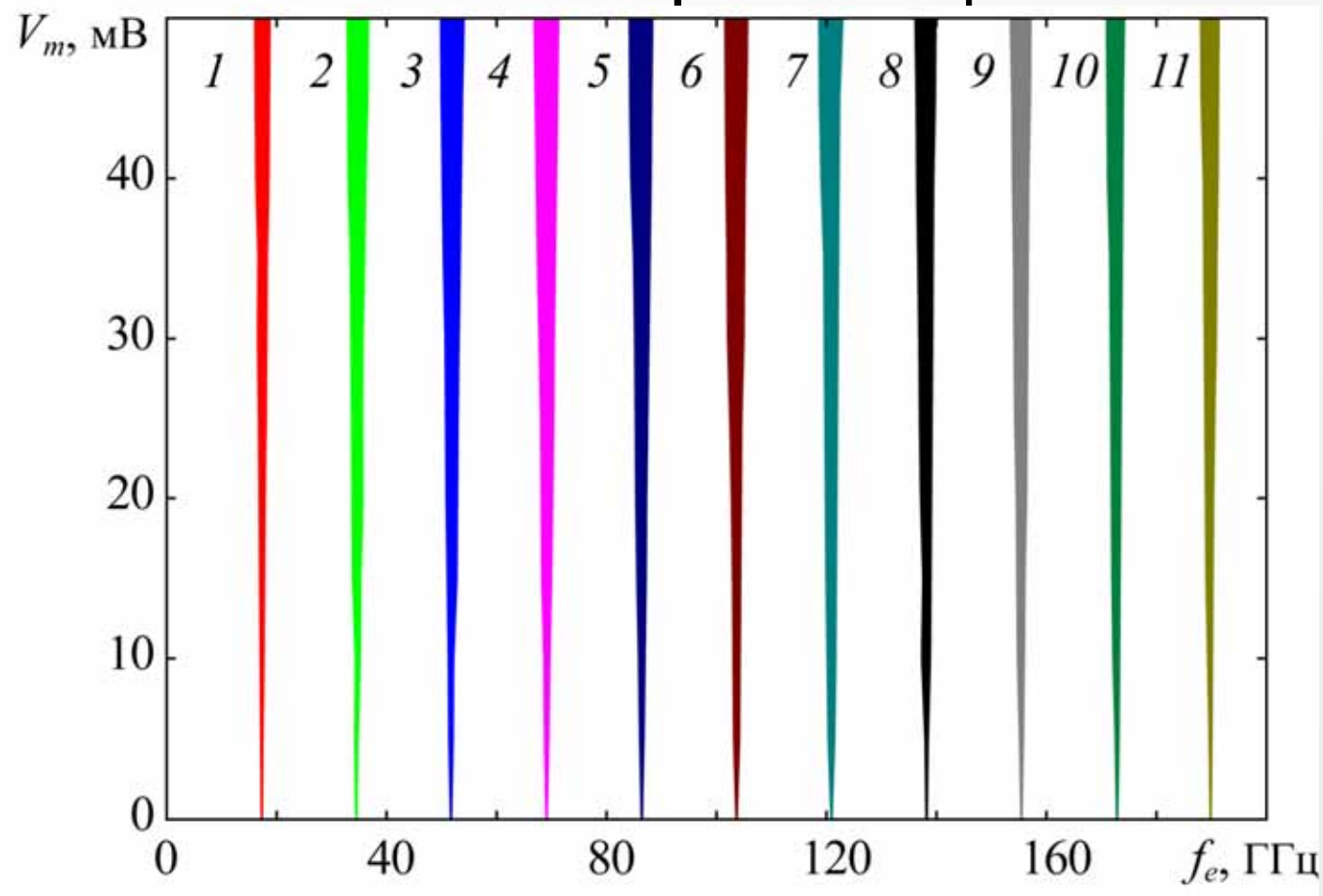
Esaki L., Tsu R. Superlattices and Negative Differential Conductivity in Semiconductors. IBM Journal of Research and Development. **14** (1) (1970) 61-65

ВАХ и число вращения



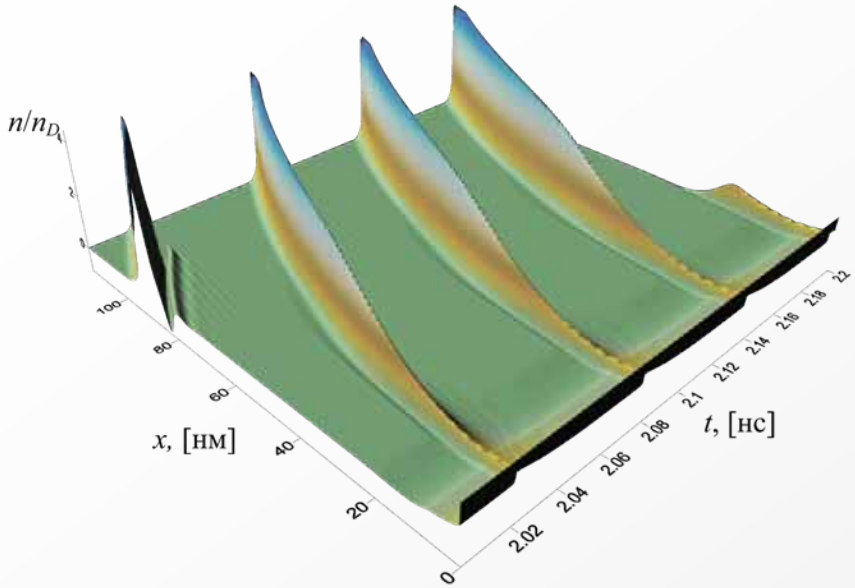
$V_m = 30$ мВ, $f_e = 17.3$ ГГц

Влияние параметров внешнего воздействия на установление синхронизации

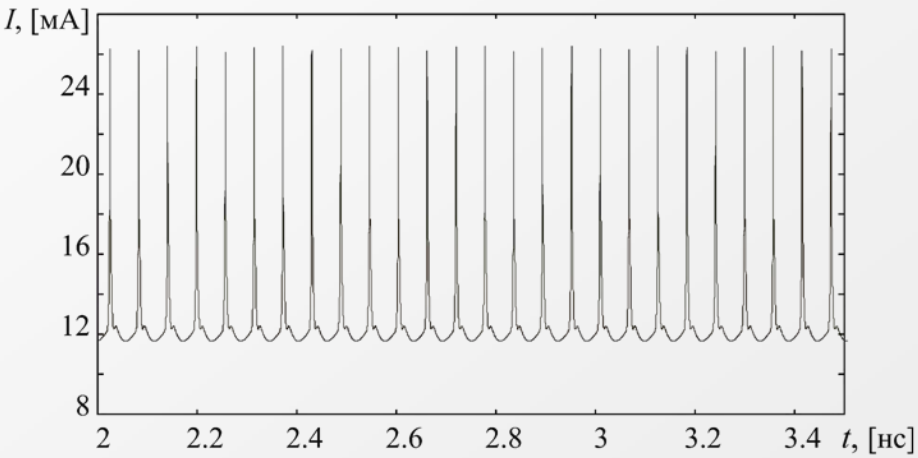


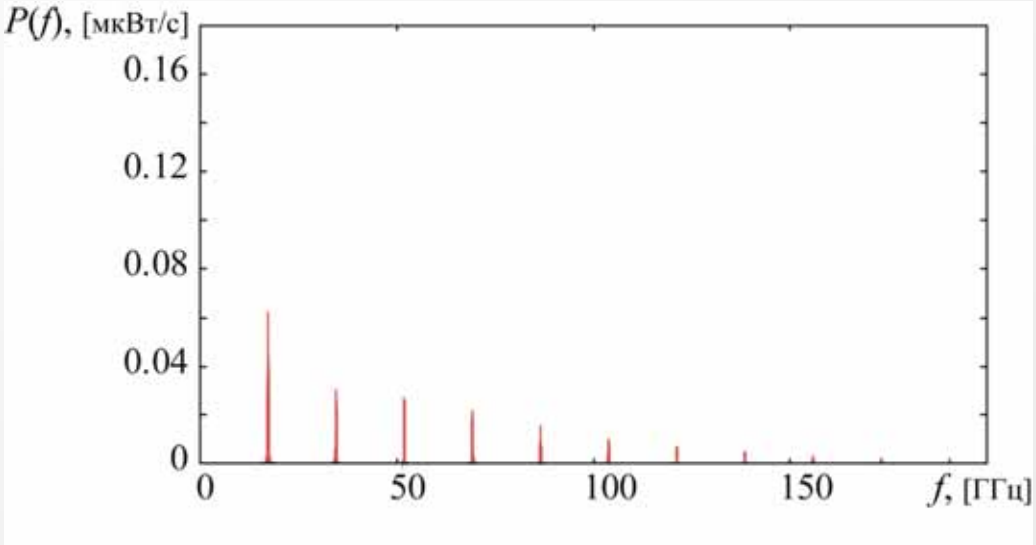
$V_0 = 510$ мВ

Динамика концентрации заряда и колебаний тока



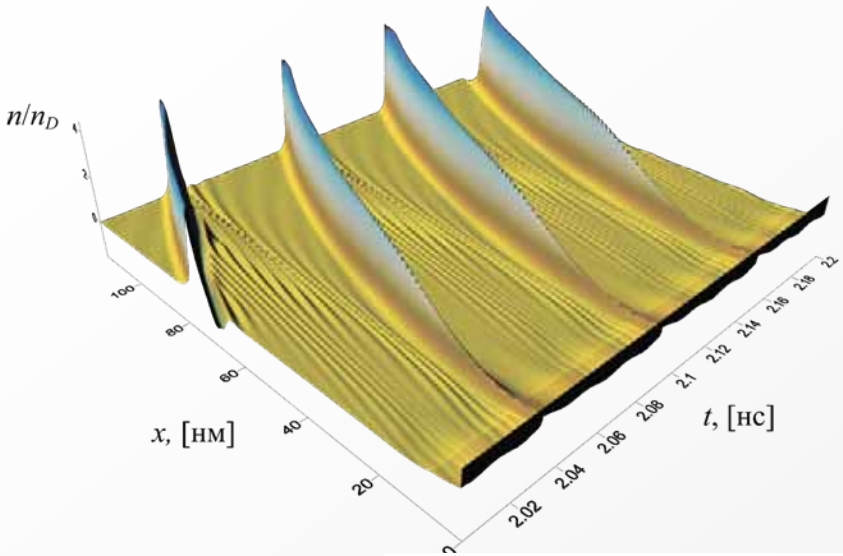
$V_m = 0$

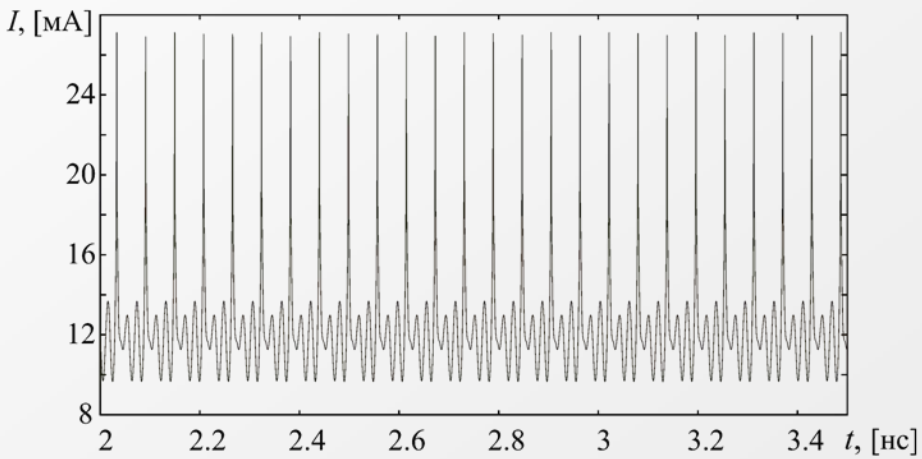


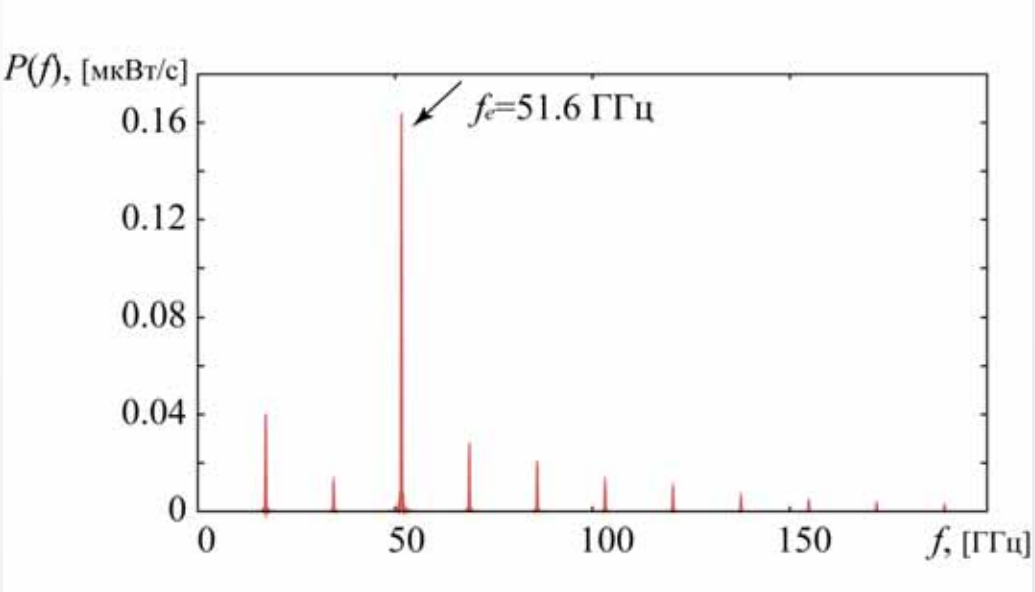


Динамика концентрации заряда и колебаний тока

$V_m = 50$ мВ, $\rho = 3$

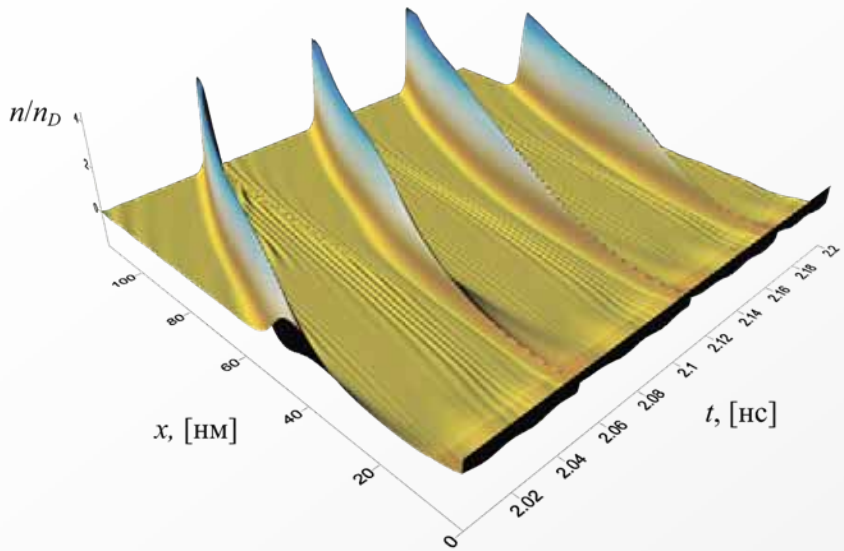


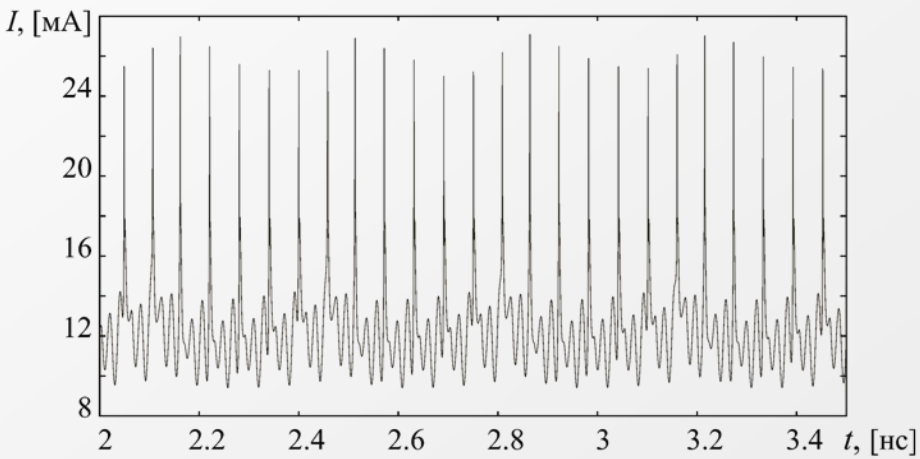


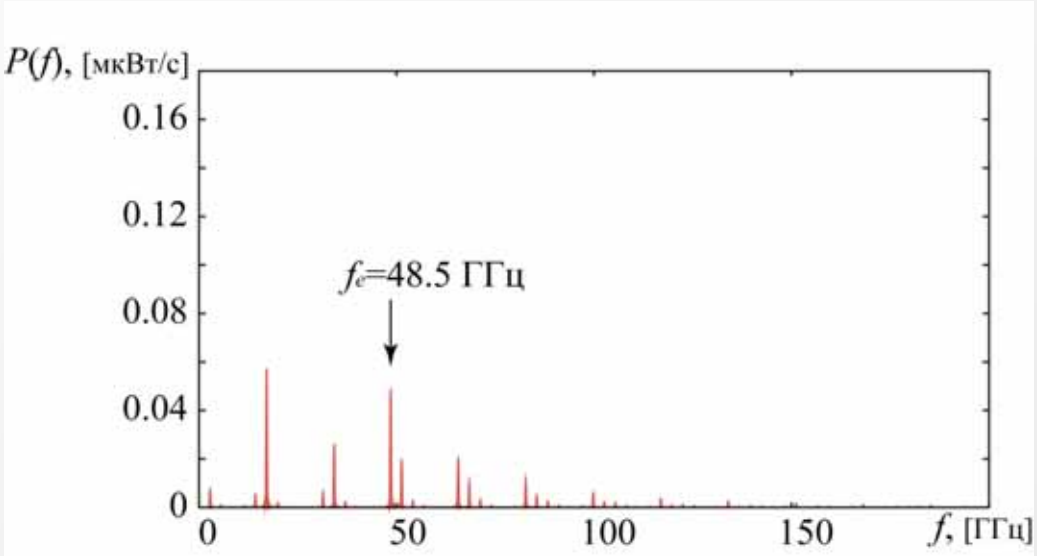


Динамика концентрации заряда и колебаний тока

V_m=50 мВ, ρ=2.84







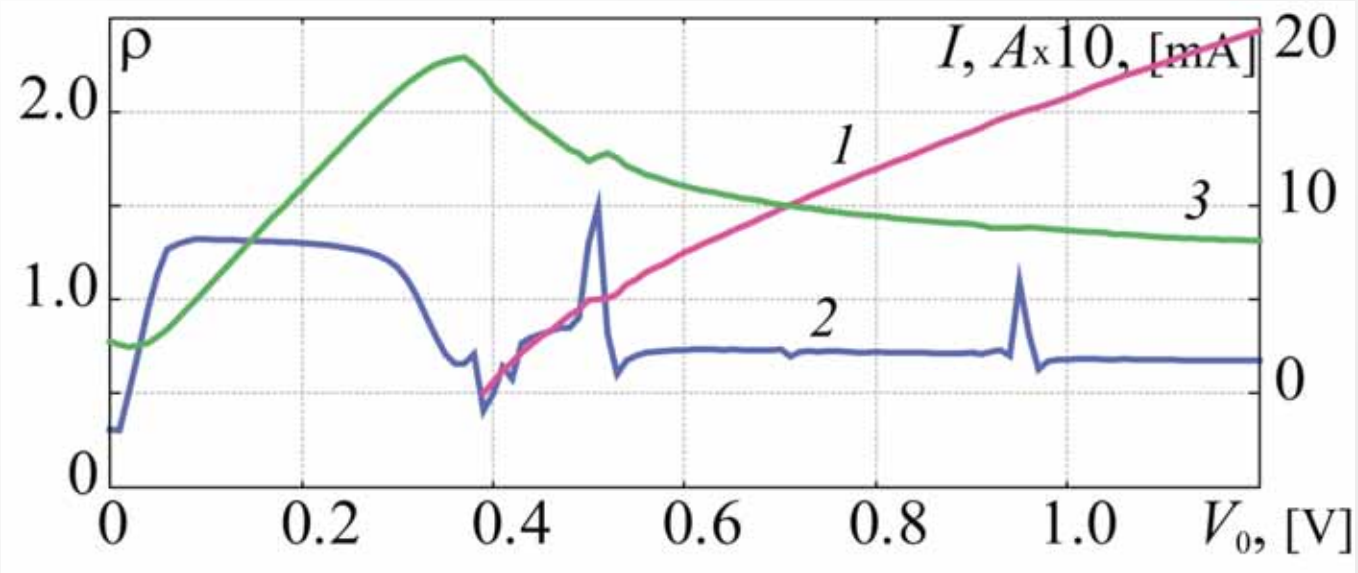
Поглощение мощности на частоте внешнего воздействия (абсорбция)

$$A(\omega_e) = \langle I(t)\cos(\omega_e t)\rangle_t,$$

Традиционный коэффициент поглощения $\sigma(см^{-1}) = \frac{2}{n_r \varepsilon_0 c}\frac{A}{V_m}$

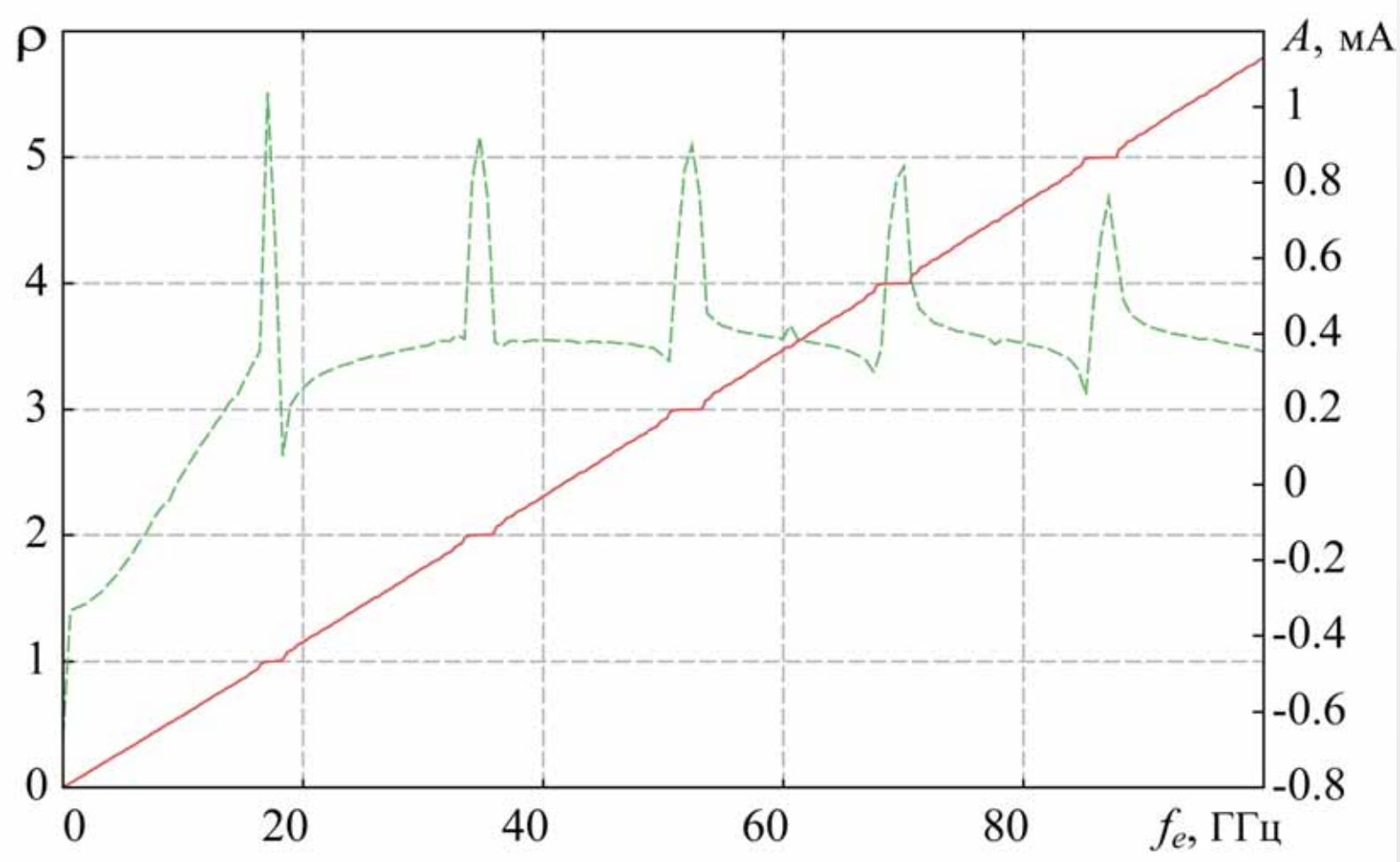
A > 0 – поглощение на данной частоте

A < 0 – вынужденное (стимулированное) излучение на заданной частоте в перпендикулярном к сверхрешетке направлении



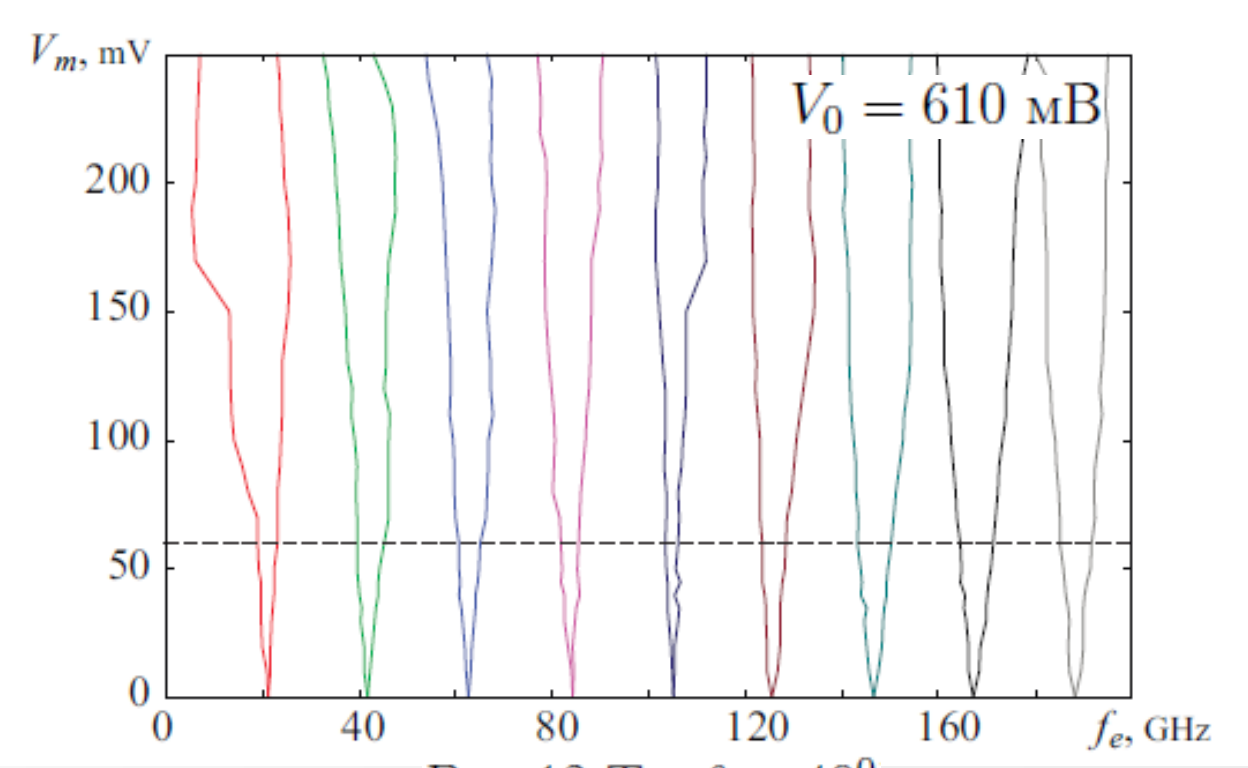
Hyart T., Alekseev K., Thuneberg E. Bloch gain in DC-AC-driven semiconductor superlattices in the absence of electric domains. Physical Review B. **77** (16) (2008), 165330.

Абсорбция и число вращения в зависимости от частоты внешнего воздействия



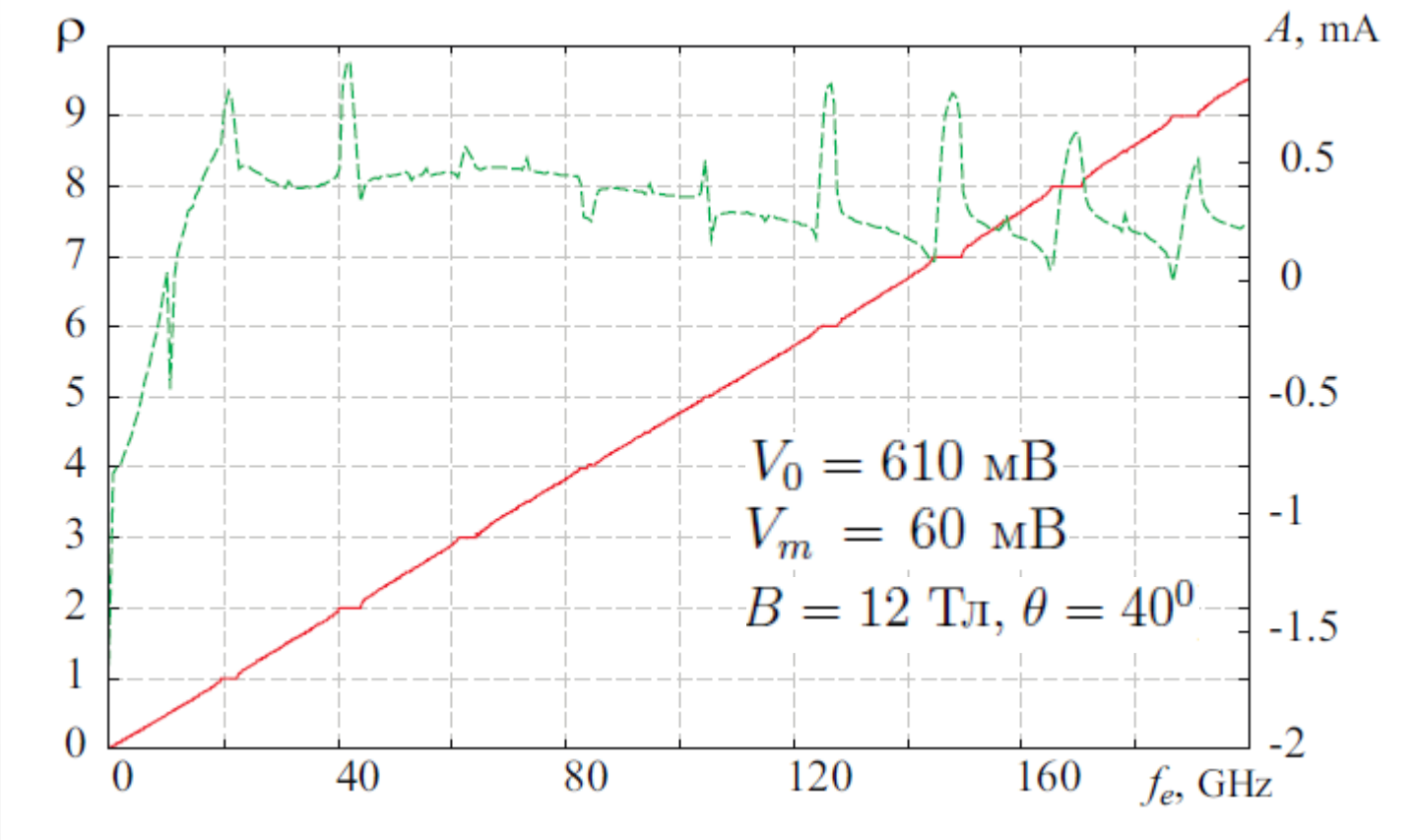
$V_0 = 510$ мВ, $V_m = 30$ мВ

Синхронизация в присутствии наклонного магнитного поля

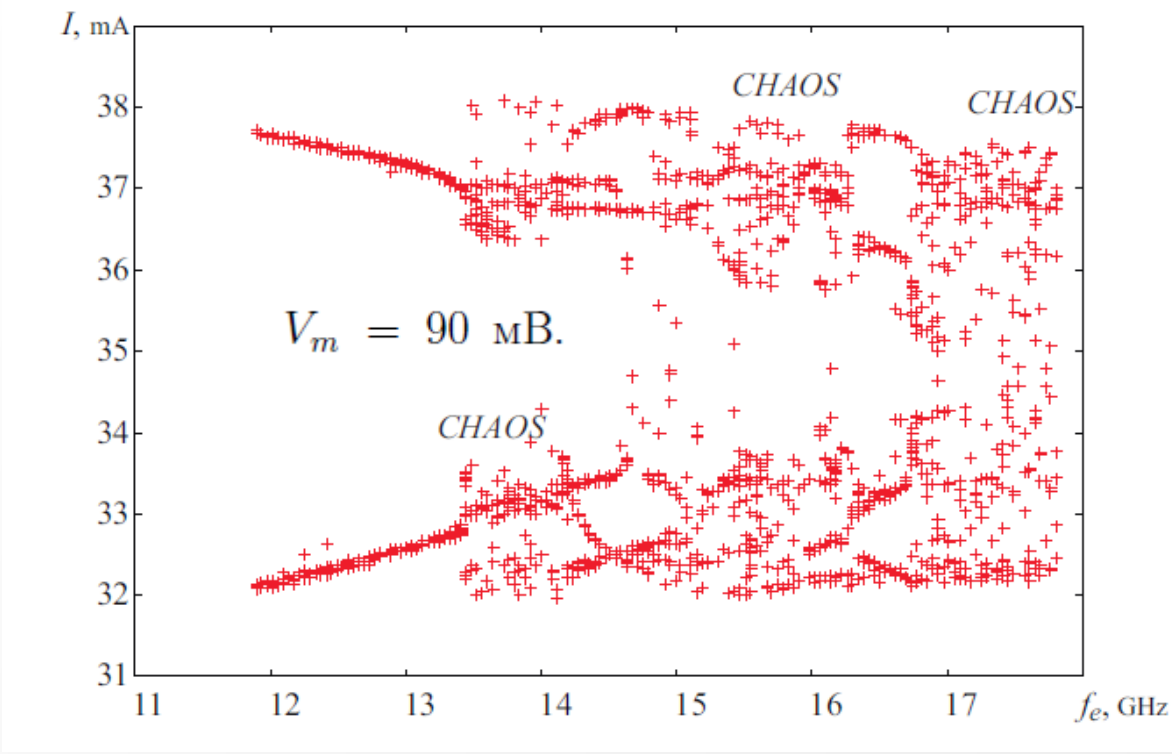


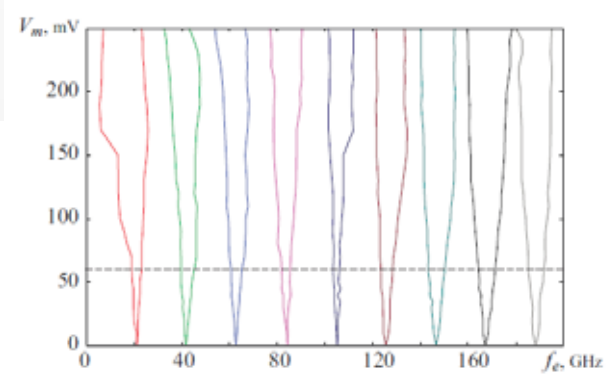
$B = 12$ Тл, $\theta = 40^0$

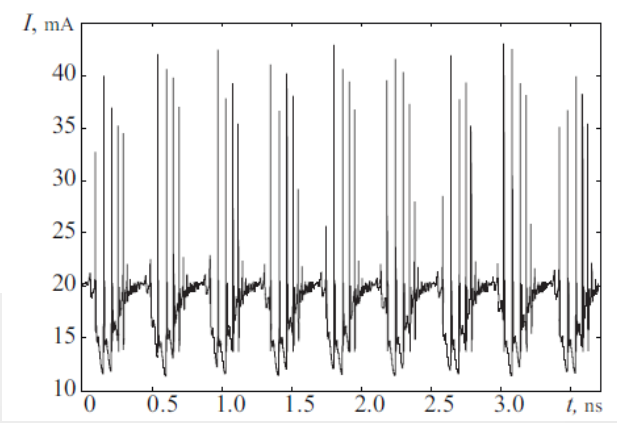
Синхронизация в присутствии наклонного магнитного поля



Сложные режимы, индуцированные воздействием, при наклонном магнитном поле







Выводы

- Показано, что слабый внешний периодический сигнал может эффективно синхронизовать движение доменов в полупроводниковой сверхрешетке, что сопровождается резким увеличением поглощения.

- В отсутствии наклонного магнитного поля ширина зон синхронизации практически не зависит от отношения частот следования доменов и воздействия.

- Наклонное магнитное поле может существенно влиять на синхронизацию движения доменов в сверхрешетке и приводить к возникновению хаотических колебаний тока.