Terahertz magnetospectroscopy of two-dimensional plasma oscillations in GaN/AlGaN heterostructures

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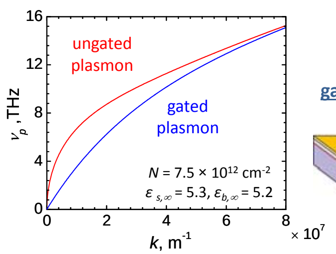
*Lecture on **Selected aspects of nanotechnology***

Outline

Excitation of plasmons in 2DEG

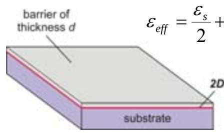
2D case: $\omega_p^2 = \dfrac{Ne^2}{2m^*\varepsilon_0\varepsilon_{eff}}k$

F. Stern, *Phys. Rev. Lett.* **18**, 546 (1967)



ungated 2DEG:

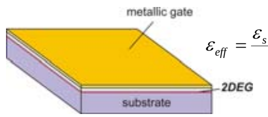
$$\varepsilon_{eff} = \frac{\varepsilon_s}{2} + \frac{\varepsilon_b}{2}\cdot\frac{1+\varepsilon_b\tanh(kd)}{1+\tanh(kd)}$$



N. Okisu et al., *App. Phys. Lett.* **48**, 776 (1986)

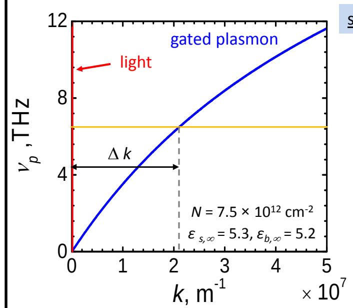
gated 2DEG:

$$\varepsilon_{eff} = \frac{\varepsilon_s + \varepsilon_b\coth(kd)}{2}$$

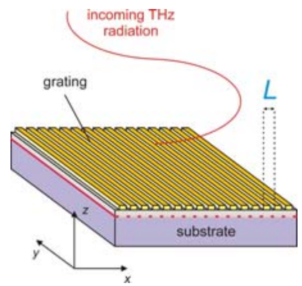


A. V. Chaplik, *Zh. Eksp. Teor. Fiz.* **62**, 746 (1972)
[*Sov. Phys. JETP* **35**, 395 (1972)]

Excitation of plasmons in 2DEG



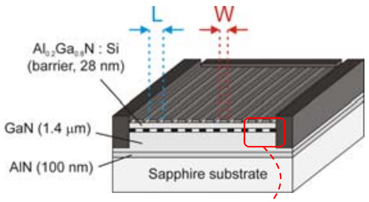
standard system intended for plasmon excitations



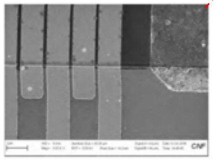
diffraction of the incident THz radiation on the grating → generation of in-plane waves with ***k*** vectors:

$k_{x,n} = nG$ $G = 2\pi / L$ $n = 1, 2, 3, \ldots$

Grating-gate transistor structures



SEM image

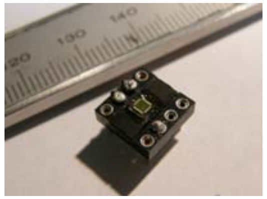


N. Pala et al., *Proc. of IEEE Sensors Conf.*, Atlanta, GA, October 2007, 291-292 (2007)

- **Growth & processing:**
  R. Gaska & J. Yang
  Sensor Electronic Technology, Inc., Columbia, South Carolina, USA
- GaN/AlGaN heterostructure grown by ***M**igration **E**nhanced **M**etal-**O**rganic **C**hemical **V**apor **D**eposition*
- Si doping of $Al_{0.2}Ga_{0.8}N$ barrier layer of $d = 28 \pm 2$ nm thickness: 2×10^{18} cm^{-3}
- active area: 1.6 × 1.6 mm²

4 grating structures:
L: 2.5 µm, 3.0 µm, 3.5 µm, 4.0 µm
S: 0.35 µm or 0.85 µm
W = L - S

\+ reference structure without a gate/grating



First experiments (without magnetic field)

APPLIED PHYSICS LETTERS 96, 042105 (2010)

Temperature dependence of plasmonic terahertz absorption in grating-gate gallium-nitride transistor structures

A. V. Muravjov,[1,2,a] D. B. Veksler,[1] V. V. Popov,[3] O. V. Polischuk,[3] N. Pala,[4] X. Hu,[5] R. Gaska,[5] H. Saxena,[6] R. E. Peale,[6] and M. S. Shur[1]
[1]Department of Electrical, Computer and Systems Engineering, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
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[4]Electrical and Computer Engineering, Florida International University, Miami, Florida 33174, USA
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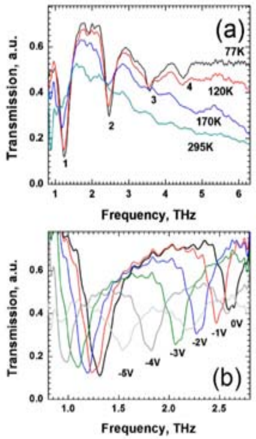
Strong plasmon resonances have been observed in the terahertz transmission spectra (1–5 THz) of large-area slit-grating-gate AlGaN/GaN-based high-electron-mobility transistor (HEMT) structures at temperatures from 10 to 170 K. The resonance frequencies correspond to the excitation of plasmons with wave vectors equal to the reciprocal lattice vectors of the metal grating, which serves both as a gate electrode for the HEMT and a coupler between plasmons and incident terahertz radiation. Wide tunability of the resonances by the applied gate voltage demonstrates potential of these devices for terahertz applications. © 2010 American Institute of Physics. [doi:10.1063/1.3292019]

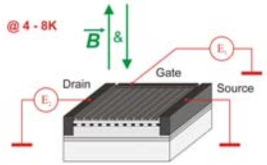
$$\omega_{p,j}^2 = \frac{Ne^2}{2m^*\varepsilon_0\varepsilon_{\text{eff}}(k_j d)}k_j \qquad \varepsilon_{\text{eff}}(k_j d) = \frac{\varepsilon_s + \varepsilon_b \,\text{ctgh}(k_j d)}{2}$$

$$k_j d \ll 1 \Rightarrow \quad \varepsilon_{\text{eff}}(k_j d) \approx \frac{\varepsilon_b}{2k_j d} \qquad \omega_{p,j}^2 \approx \frac{Ne^2 d}{m^*\varepsilon_0\varepsilon_b}k_j^2$$

the resonances. The best fit of the resonance shift versus U_g for the first, second, and third resonances in Fig. 2(b) corresponds to $U_{th}^* = -8$ V, while the value of U_{th} found from the transconductance measurements is about −4 V. We explain this by a voltage drop across the channel caused by the gate leakage current crowding at the edges of the structure. The gate leakage conductivity is about 0.005 Ω^{-1} at $T = 10$ K, while the conductivity of the channel is about 0.02 Ω^{-1} (for $U_g = 0$). As a result, the applied gate voltage $U_{g,appl}$ [specified in Fig. 2(b)] appears almost two times higher than the actual

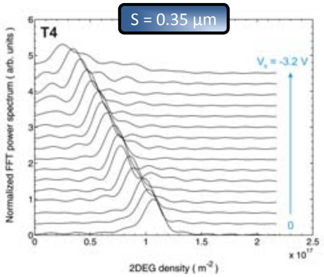


Magnetotransport characterization

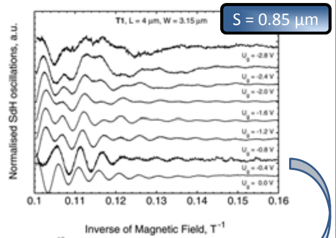


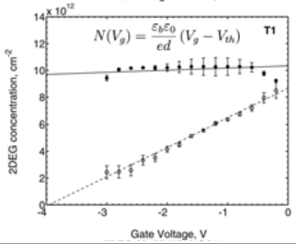
- B up to 10 T

S = 0.35 µm



S = 0.85 µm



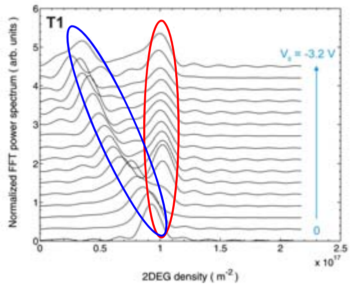


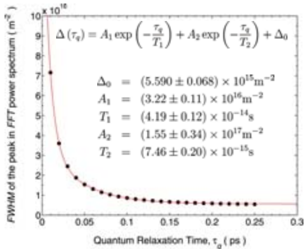
Magnetotransport characterization

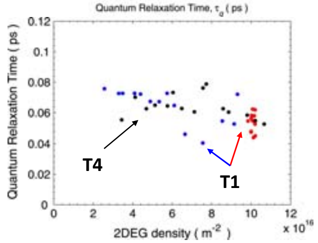
Quantum relaxation time

$$R_{SdH} \simeq R_0\left(1+\frac{4A}{\sinh A}\exp\left(-\frac{\pi m^*}{eB\tau_q}\right)\sin\left(\frac{\pi n_s h}{eB}+\phi\right)\right)$$

$$A = \frac{4\pi^3 k_B T m^*}{heB}$$

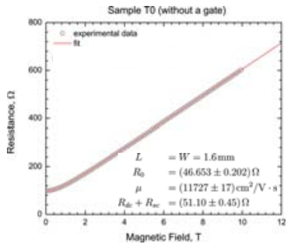


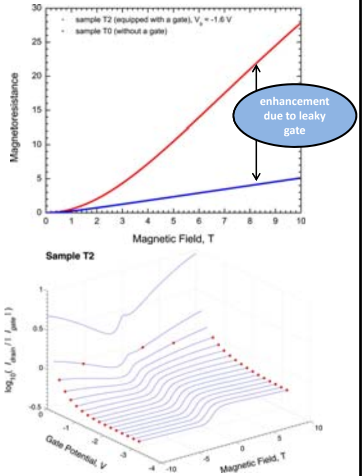




Magnetotransport characterization

Gate-leakage current induced geometrical magnetoresistance





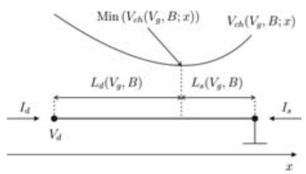
$$R(B) = \frac{V_d}{I_{ds}(B)} = \frac{V_d}{I_d(B)} = R_0\sqrt{1+\mu^2B^2} + R_{dc} + R_{sc}$$

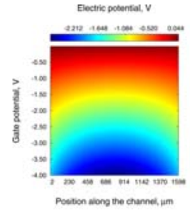
R. F. Wick, *J. Appl. Phys.* **25**, 741 (1954), H. J. Lippmann and F. Kuhrt, *Z. Naturforsch.* **13a**, 462 (1958), H. J. Lippmann and F. Kuhrt, *Z. Naturforsch.* **13a**, 474 (1958), R. W. Rendell and S. M. Girvin, *Phys. Rev. B* **23**, 6610 (1981), M. M. Parish and P. B. Littlewood, *Phys. Rev. B* **72**, 094417 (2005)

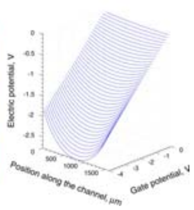
Magnetotransport characterization

Gate-leakage current induced geometrical magnetoresistance

- resistor-network model of a transitor with a leaky gate electrode:







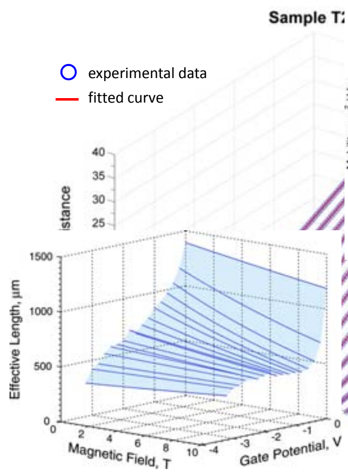
$$\frac{I_d(0)}{I_d(B)} = \frac{V_d - \mathrm{Min}\left(V_{ch}(V_g,B;x)\right)}{V_d - \mathrm{Min}\left(V_{ch}(V_g,0;x)\right)} \cdot \frac{\sqrt{1+\mu^2B^2}F_{L_d,W,\mu}(B) + \frac{R_{contact}}{R_0}}{1+\frac{R_{contact}}{R_0}} \simeq \sqrt{1+\mu^2B^2}F_{L'_d,W,\mu}(B)$$

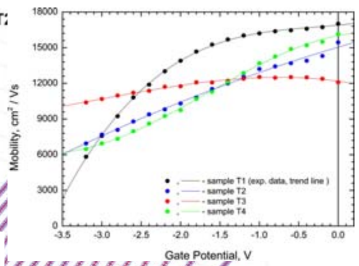
$$F_{L,W,\mu_{GMR}}(B) = \frac{\int_0^1 dx\cos\left(\Theta_{WL}(x)\right)}{\int_0^1 dx\cos\left(\Theta_{LW}(x)\right)} \qquad \Theta_{WL}(x) = \sum_{n\,(odd)} \frac{4\,\mathrm{arctg}(\mu_{GMR}B)}{n\pi}\frac{\sin(n\pi x)}{\cosh\left(\frac{n\pi}{2}\frac{W}{L}\right)}$$

Fitting procedure:

1. for $B \le 0.15$ T: $\sqrt{1+\mu^2B^2} \approx 1 + \frac{1}{2}\mu^2B^2$
2. $L'_d(B) = L_0\exp\left(-\frac{B}{B_0}\right)$

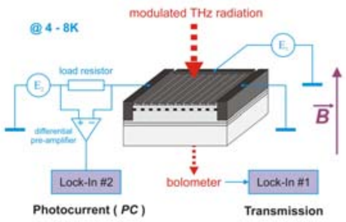
Magnetotransport characterization





<u>quantitatively</u>, final conclusions in the form of estimated mobility, 2DEG concentration and quantum relaxation time correct only for a limited area of the GaN/AlGaN quantum well, but <u>qualitatively</u> true for the entire sample

Magnetooptical experiments

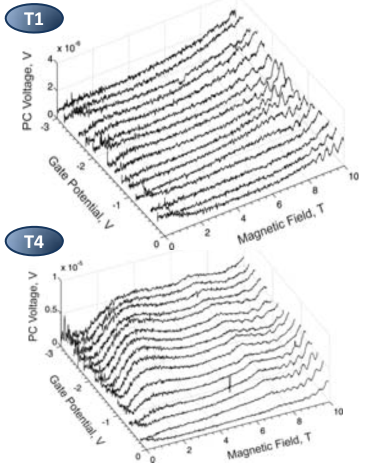


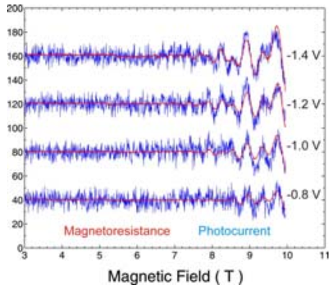
- T = 4.2 – 8 K
- ***B*** up to 10 T

1. transmission of 2.52 THz radiation measured as a function of the gate voltage (U_g) at a given ***B***
2. transmission of 2.52 THz radiation & PC measured <u>simultaneously</u> as a function of ***B*** at a given U_g

- low-noise, adjustable power supply for bolometer, equipped with symmetric voltage stabilizers based on *LM317* and *LM337* positive and negative voltage regulators and 9V batteries
- low-noise differential pre-amplifier for photocurrent measurements and voltage summator, based on precise *OP27* operational amplifiers
- well-defined common potential for all BNC conncectors

Magnetooptical experiments - photocurrent





DC current ~ 10 mA
Photocurrent ~ 1-10 nA

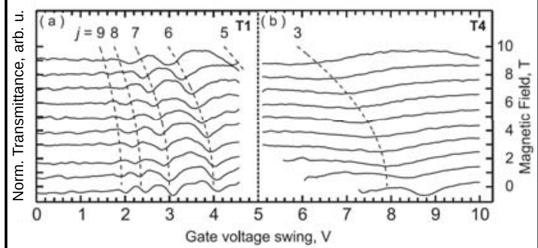
Magnetooptical experiments - Transmission vs U_{gate}

ν_{FIR} = 2.52 THz

$k_j=(2j-1)\cdot\pi/W_{eff}$

Sample	L (µm)	W (µm)	S (µm)
T1	4.0	3.15	0.85
T4	2.5	2.15	0.35

$k_j=(2\pi/L)\cdot j$



large inter-finger spacing (S)
excitation of localized/confined gated magnetoplasmon modes

small inter-finger spacing (S)
excitation of delocalized/collective gated magnetoplasmon modes

K. Nogajewski et al., *Appl. Phys. Lett.* **99**, 213501 (2011)

1. $\omega_{p,j}^2(B)=\omega_{p,j}^2(B=0)+\omega_c^2$

T. N. Theis, *Surf. Sci.* **98**, 515 (1980)
A. V. Chaplik, *Surf. Sci. Rep.* **5**, 289 (1985)

2. $\omega_{p,j}^2(B=0)=\frac{Ne^2}{2m^*\varepsilon_0\varepsilon_{eff}}k_j$

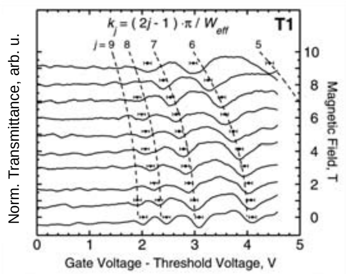
3. $\varepsilon_{eff}=\frac{\varepsilon_s+\varepsilon_b\coth(k_j d)}{2}$

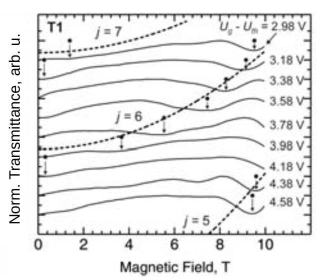
4. $N(U_{gate})=\alpha\cdot(U_{gate}-U_{th})$

Magnetooptical experiments

Transmission vs. U_{gate} @ constant ***B***

Transmission vs. ***B*** @ constant U_{gate}

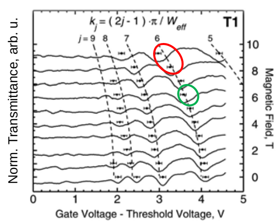




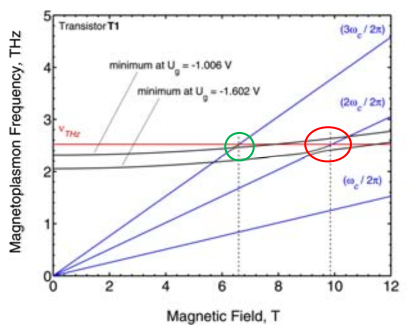
- good correspondence between two complementary types of transmission experiments
- satisfying description of experimental results provided by a relatively simple theoretical model

Magnetooptical exp. – deviations from simple model

Transmission vs U_{gate} @ constant ***B***



V_{th} = -4.58 V

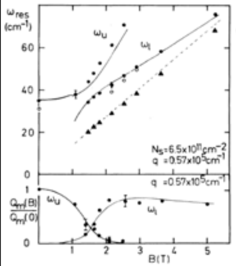


Excitation of so-called *Bernstein modes* as an explanation of discrepancy between the experimental data and the simple theoretical description?

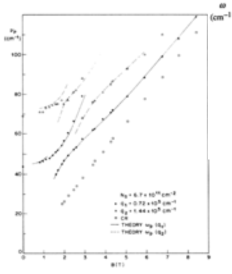
I. B. Bernstein, *Phys. Rev.* **109**, 10 (1958)

Bernstein modes in other materials

GaAs/AlGaAs heterostructures

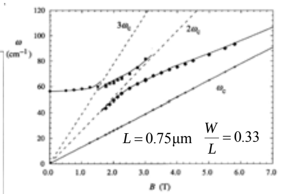


E. Batke et al., *Phys. Rev. Lett.* **54**, 2367 (1985)



E. Batke et al., *Phys. Rev. B* **34**, 6951 (1986)

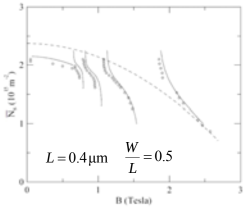
$L \approx 0.83\mu m$



D. E. Bangert et al., *Semicond. Sci. Technol.* **11**, 352 (1996)

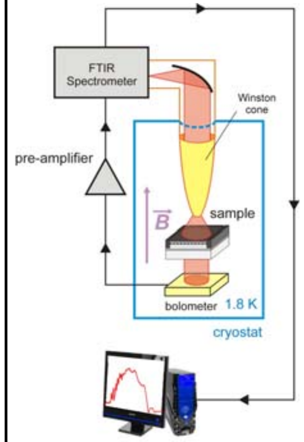
- silicon inversion layers

T. N. Theis et al., *Solid State Commun.* **24**, 273 (1985)



J. Lefebvre et al., *Semicond. Sci. Technol.* **13**, 169 (1998)

Fourier Transform Infrared (FTIR) Magnetospectroscopy

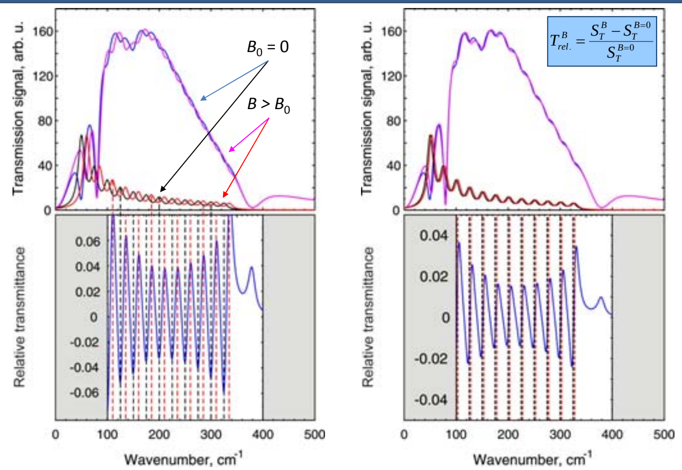


close cooperation with **M. Orlita** and **M. Potemski** from the GHMFL and **A. Witowski** from the Faculty of Physics of the University of Warsaw

- *Bruker IFS* 113v spectrometer coupled with the magnetic field up to 13 T
- transmission measured by a sensitive silicon bolometer:
  - for different values of ***B*** and floating source, drain and gate electrodes
  - for different values of U_g at a constant value of ***B***
- T = 1.8 K
- spectral range: 20 cm^{-1} – 500 cm^{-1}

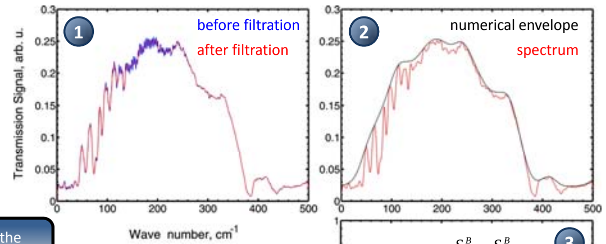
(mercury lamp as a source of far-infrared radiation + T222 beam-splitter)

Experimental Data Treatment



Experimental Data Treatment

MATLAB 7.10.0
(R2010a)

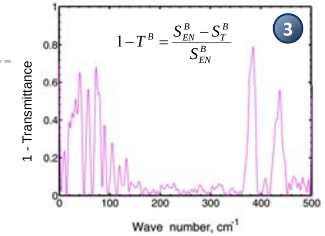


Modelling the spectrum envelope:

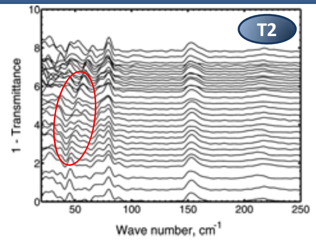
procedure based on iterative application of the Savitzky-Golay filtering (smoothing) algorithm combined with the following criterion:

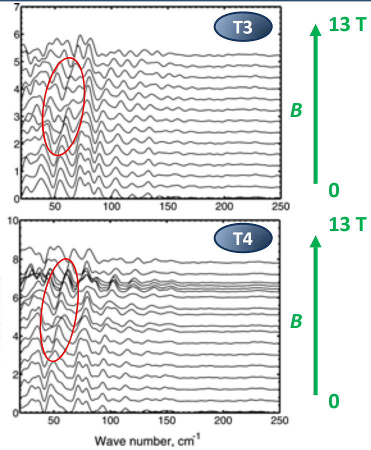
$$S^j_{EN,a}(\lambda_i^{-1}) \geq S_T(\lambda_i^{-1}) \Rightarrow S^{j+1}_{EN,b}(\lambda_i^{-1}) = S^j_{EN,a}(\lambda_i^{-1})$$

$$S^j_{EN,a}(\lambda_i^{-1}) < S_T(\lambda_i^{-1}) \Rightarrow S^{j+1}_{EN,b}(\lambda_i^{-1}) = S_T(\lambda_i^{-1})$$



Results of FTIR Magnetospectroscopy





Sample	L (μm)	W (μm)	$c = (W / L)$
T2	3.0	2.15	0.7167
T3	3.5	3.15	0.9
T4	2.5	2.15	0.86

Experimental Data Treatment - *FSD*

Fourier Self-Deconvolution (*FSD*)

function determining the shape of spectral lines

spectrum without line broadening

- experimental spectrum: $E(\tilde{\nu}) = G(\tilde{\nu}) * \tilde{E}(\tilde{\nu}) = \int_{-\infty}^{+\infty} G(\tilde{\nu}')\tilde{E}(\tilde{\nu}-\tilde{\nu}')\,\mathrm{d}\tilde{\nu}'$
- in the real space: $I(x) = F^{-1}\{E(\tilde{\nu})\} = \int_{-\infty}^{+\infty} E(\tilde{\nu})\exp(\text{-}2\pi i\tilde{\nu}x)\,\mathrm{d}\tilde{\nu}$
- normal/inverse Fourier transform of the convolution of two functions is equal to the product of normal/inverse Fourier transforms of each function

$$I(x) = F^{-1}\{G(\tilde{\nu})\}\cdot F^{-1}\{\tilde{E}(\tilde{\nu})\}$$

so: $$\tilde{E}(\tilde{\nu}) = F\left\{\frac{I(x)}{F^{-1}\{G(\tilde{\nu})\}}\right\} = F\left\{\frac{F^{-1}\{E(\tilde{\nu})\}}{F^{-1}\{G(\tilde{\nu})\}}\right\}$$

- more complicated reality:

$$\tilde{E}_{imp}(\tilde{\nu}) = F\left\{\frac{D_a(x)I(x)}{F^{-1}\{G(\tilde{\nu})\}}\right\} = F\left\{\frac{D_a(x)F^{-1}\{E(\tilde{\nu})\}}{F^{-1}\{G(\tilde{\nu})\}}\right\}$$

apodization function

<u>Most commonly observed profiles of spectral lines:</u>

Lorentz's profile: $L(\nu;\gamma) \equiv \dfrac{\gamma}{\pi(\nu^2+\gamma^2)}$

$$F^{-1}\{L(\nu;\gamma)\} = \exp(-2\pi\gamma\,|\,x\,|)$$

Gauss's profile: $G(\nu;\sigma) \equiv \dfrac{1}{\sqrt{2\pi}\sigma}\exp\left(-\dfrac{\nu^2}{2\sigma^2}\right)$

$$F^{-1}\{G(\nu;\sigma)\} = \exp(-2\pi^2\sigma^2x^2)$$

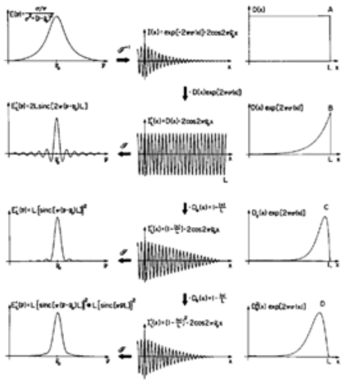
Voigt's profile: $V(\nu;\gamma,\sigma) \equiv L(\nu;\gamma) * G(\nu;\sigma)$

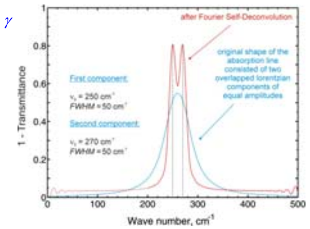
$$F^{-1}\{V(\nu;\gamma,\sigma)\} = F^{-1}\{L(\nu;\gamma)\}\cdot F^{-1}\{G(\nu;\sigma)\}$$

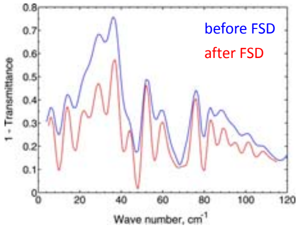
J. K. Kauppinen et al., *Appl. Spectrosc.* **35**, 271 (1981)
J. K. Kauppinen et al., *Anal. Chem.* **53**, 1454 (1981)
J. K. Kauppinen et al., *Appl. Opt.* **20**, 1866 (1981)
J. K. Kauppinen et al., *Appl. Opt.* **21**, 1866 (1982)

Experimental Data Treatment - *FSD*

- input parameters for the *FSD* procedure: profile, L, σ, γ

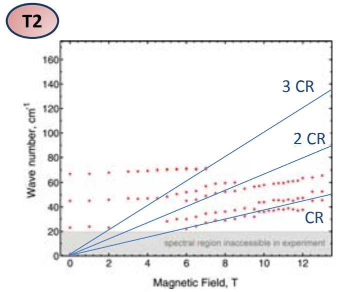


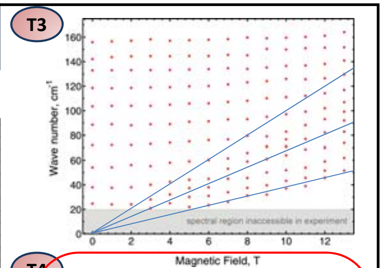


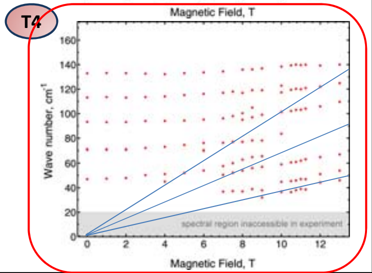


J. K. Kauppinen et al., *Appl. Spectrosc.* **35**, 271 (1981)

Results of FTIR Magnetospectroscopy







Sample	L (μm)	W (μm)	$c = (W / L)$
T2	3.0	2.15	0.7167
T3	3.5	3.15	0.9
T4	2.5	2.15	0.86

I. B. Bernstein, *Phys. Rev.* **109**, 10 (1958)

Description of non-local properties of an electron gas

The Model:

1. is based on a self-consistent solution of the **Boltzmann-Vlasov kinetic equation** describing the motion of electrons forming a plasma subject to an external magnetic field
2. includes the long-range Coulomb interaction between electrons in the form of self-consistent electric field
3. neglects: local-field corrections, correlation effects, exchange and short-range Coulomb interactions between electrons
4. assumes validity of the relaxation time, effective mass and random phase approximations
5. focuses on long-wavelength plasma excitations

$$\frac{\partial f}{\partial t}+[\mathbf{u}\cdot\nabla+e(\mathbf{E}+\mathbf{u}\times\mathbf{B})\cdot\nabla_p]\,f=\left(\frac{\partial f}{\partial t}\right)_{\text{coll.}}$$

+ Maxwell's equations

$$\frac{\partial f}{\partial t}+[\mathbf{u}\cdot\nabla+e(\mathbf{E}+\mathbf{u}\times\mathbf{B})\cdot\nabla_p]\,f=-\frac{f-f^0(\mathbf{p})}{\tau}$$

$$f\equiv f(\mathbf{p},\mathbf{r},t)=f^0(\mathbf{p})+\delta f(\mathbf{p},\mathbf{r},t)\qquad \mathbf{u}\equiv\frac{\mathbf{p}}{m^*}$$

⇓

$$\mathbf{j}(\mathbf{k},\omega)=\frac{e}{(2\pi)^3}\int(\mathbf{p}/m^*)\delta f(\mathbf{p},\mathbf{k},\omega)\mathrm{d}^3\mathbf{p}$$

$$\mathbf{j}(\mathbf{k},\omega)=\sigma(\mathbf{k},\omega)\mathbf{E}$$

⇓

$$\hat{\varepsilon}(\omega,\mathbf{k})=\varepsilon_{lattice}(\omega)+\frac{i\hat{\sigma}(\omega,\mathbf{k})}{\omega\varepsilon_0}$$

$$\varepsilon_{xx}(\omega,\mathbf{k})=0$$

Description of non-local properties of an electron gas

- implicit dependence on k of $\sigma(\omega, \mathbf{k})$ through $\omega_p(k)$ and so-called non-local parameter

$$X_j=k_j\frac{u_F}{\omega_c}=\frac{k_j m^* u_F}{eB}=k_jR_c=2\pi\frac{R_c}{\lambda_j}$$

X_j → measure of the extent to which the cyclotron motion of electrons probes the spatially non-uniform electric field of the plasma wave

- $X_j\to 0 \Leftrightarrow$ local limit
- $X_j\approx 1 \Leftrightarrow$ strong non-local effects

- estimation of the X parameter for the **T4** sample:

$N=8.8\times10^{16}\ \mathrm{m}^{-2}\qquad m^*=0.22\,m_0 \;\Rightarrow\; u_F=\frac{\hbar}{m^*}(2\pi N)^{1/2}=3.91\times10^5\ \mathrm{m/s}$

$L=2.5\,\mu\mathrm{m}\qquad j=2\qquad k_j=\frac{2\pi}{L}j\qquad B=8\mathrm{T} \;\Rightarrow\; X_2(B{=}8\mathrm{T})\approx0.31$

Non-local dispersion of 2D magnetoplasmons

$$\varepsilon_\infty\frac{\omega^2-\omega_{LO}^2}{\omega^2-\omega_{TO}^2}-\varepsilon_\infty\omega_p^2(k_j)\frac{6}{X_j^2}\sum_{n=1}^{\infty}\frac{n^2g_n(X_j)}{\omega^2-(nf_n\omega_c)^2}=0$$

for a given B and j, polynomial function of ω, which roots correspond to magnetoplasmon resonances

$$X_j=k_j\frac{u_F}{\omega_c}=\frac{k_j m^* u_F}{eB}=k_jR_c=2\pi\frac{R_c}{\lambda_j}\qquad g_n(X_j)=\frac{1}{X_j}\int_0^{X_j}J_{2n}(2\xi)d\xi$$

$$\omega_p^2(k_j)=\frac{Ne^2}{2m^*\varepsilon_0\varepsilon_{eff}(k_j)}k_j\qquad k_j=\frac{2\pi}{L}j$$

known from magnetotransport measurements (appropriately corrected due to leaky gate effects for non-zero V_g)

known grating parameter

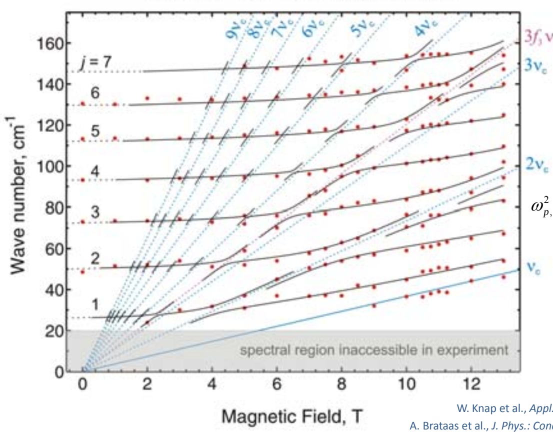
$\varepsilon_{s,\infty}$ = 5.3 (GaN) $\varepsilon_{b,\infty}$ = 5.2 ($Al_{0.2}Ga_{0.8}N$) n = 1, 2, 3,..., 9 $f_1\equiv1$ f_2 = 1

ν_{LO} = 742 cm^{-1} (GaN) ν_{TO} = 560 cm^{-1} (GaN)

⇒ only **3** fitting parameters: m^*, u_F, f_3

Interpretation & discussion

Transistor T4: L = 2.5 μm, W = 2.15 μm



non-local approach ⇕ $X_j\to0$

υ_F = 4.7×10^5 m/s

f_3 = 1.08

$$\omega_{p,j}^2(B)=\omega_{p,j}^2+\omega_c^2(B)$$

m^* = 0.25m_0

W. Knap et al., *Appl. Phys. Lett.* **70**, 2123 (1997)
A. Brataas et al., *J. Phys.: Condens. Matter* **8**, 4797 (1996)

Interpretation & discussion

Sample	L (µm)	W (µm)	$c = (W / L)$
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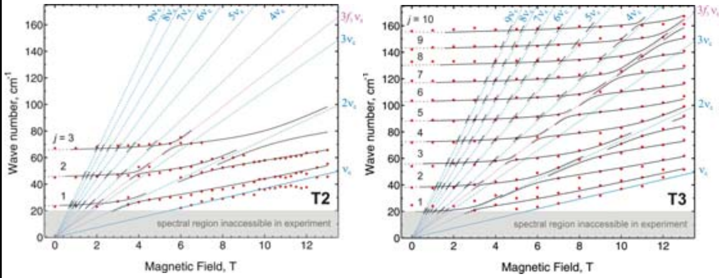
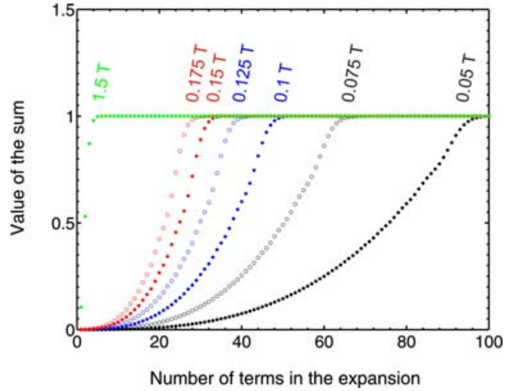
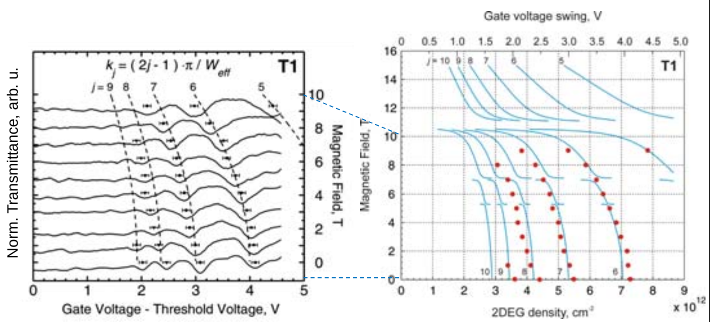


Breakdown of the model at low *B*?

$$1-\omega_p^2(k_j)\frac{6}{X_j^2}\sum_{n=1}^{\infty}\frac{n^2 g_n(X_j)}{\omega^2-(n f_n\omega_c)^2}=0 \xrightarrow{\text{low } B} 1-\frac{\omega_p^2(k_j)}{\omega^2}\sum_{n=1}^{\infty}\frac{6n^2 g_n(X_j)}{X_j^2}\cong 0 \qquad \sum_{n=1}^{\infty}\frac{6n^2 g_n(X_j)}{X_j^2}\to 1$$



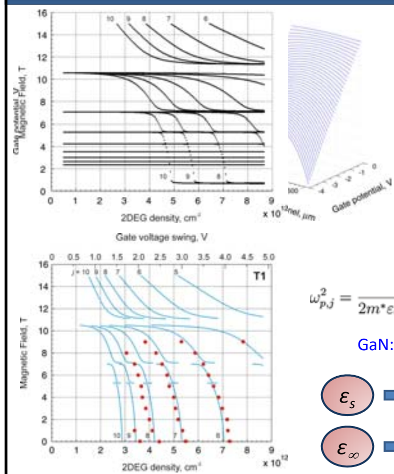
Solutions to the riddles



Current experimental capabilites of *TQP & FIR Laboratory* at the Faculty of Physics of the University of Warsaw:

B **field up to 15 T**

Solutions to the riddles



contrary to the statement of A. Muravjov et al. (*Appl. Phys. Lett.* **96**, 042105 (2010)), even close to the threshold voltage and for 20 times more leaky gate electrode, there is only 25% (not 200%) difference in 2DEG density between the edges and the central part of the sample

necessity of increasing twice the square of plasma frequency – result of neglecting the lattice contribution to the dynamic dielectric function of 2DEG (overestimating the validity of long-wavelength approximation in theoretical description of plasma excitations)

$$\omega_{p,j}^2=\frac{Ne^2}{2m^*\varepsilon_0\varepsilon_{\text{eff}}(k_jd)}k_j \qquad \varepsilon_{\text{eff}}(k_jd)=\frac{\varepsilon_s+\varepsilon_b\,\text{ctgh}(k_jd)}{2}$$

GaN: $\varepsilon_\infty = 5.3$ and $\varepsilon_s = 9.2 \Rightarrow \varepsilon_s / \varepsilon_\infty = 1.736$

ε_s ⇒ control over DC electrical properties

ε_∞ ⇒ control over the optical properties

Summary

1. The first report on experimental observation of non-local interaction between 2D magnetoplasmons and CR harmonics in GaN/AlGaN heterostructures
2. The strength of non-local interaction of the same value as in the case of GaAs/AlGaAs heterostructures
3. Observation of non-local interaction between both the second and the third CR harmonic and higher order magnetoplasmon resonances (up to 7th)
4. Non-local dispersion of magnetoplasmons well described within a semi-classical model based on a solution of the Boltzmann-Vlasov kinetic equation of motion of electrons forming a plasma subjected to an external magnetic field
5. Decrease of the third harmonic cyclotron mass in comparison with the primary cyclotron mass – phenomenon not observed up to now due to lack of experimental data for higher Bernstein modes, originating probably from the band structure effects
6. Significant influence of the gate-leakage current on the effective geometry of the samples under investigation
7. Important role of lattice vibrations in correct description of plasma oscillations

Presentation and publication of the results

- *40th "Jaszowiec" 2011 International School & Conference on the Physics of Semiconductors*, June 25 - July 1, 2011, Krynica-Zdrój, Poland – oral presentation
- *36th International Conference on Infrared, Millimeter, and Terahertz Waves*, October 2 - 7, 2011, Hyatt Regency Downtown, Houston, Texas, USA – 2 oral presentations
- *1st International Symposium on Terahertz Nanoscience and 2nd Workshop of International Terahertz Research Network (GDR-I)*, November 24 - 29, 2011, Nakanoshima Center, Osaka University, Osaka, Japan – invited talk
- *41st "Jaszowiec" 2012 International School & Conference on the Physics of Semiconductors*, June 8 - 15, 2012, Krynica-Zdrój, Poland – oral presentation
- *20st International Conference on "High Magnetic Fields in Semiconductor Physics"*, July 22 - 27, 2012, Chamonix Mont-Blanc, France – poster presentation
- *31st International Conference on the Physics of Semiconductors*, July 29 – August 3, 2012, ETH Zurich, Zurich, Switzerland – oral presentation
- *OTST 2013 International Workshop on Optical Terahertz Science and Technology*, April 1 – 5, 2013, Kyoto Tersa, Japan – waiting for notification of abstract acceptance
- K. Nogajewski et al., *Appl. Phys. Lett.* **99**, 213501 (2011)
- Two manuscripts in preparation (to be submitted soon)

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JU ENIAC MERCURE project No. 220120

Thank you very much for your kind attention!

Appendix: Literature

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