laboratoire pierre aigrain
électronique et photonique quantiques

Critical Screening Field for Topological Surface States in Strained HgTe: Investigation via RF Compressiblity measurements

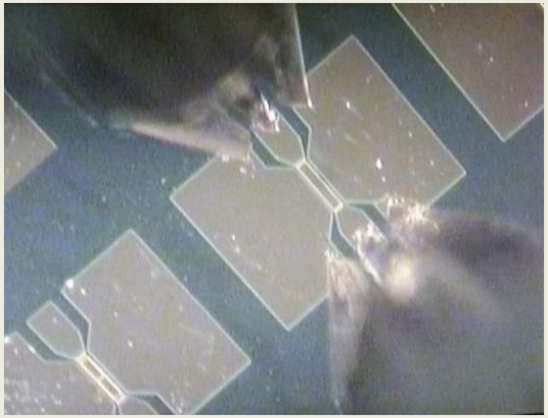
Andreas Inhofer
03/10/2016
Topolyon

Experiment:
AI, B. Assaf, G.Fève, JM. Berroir, B.Plaçais
LPA – ENS, Paris, France,

Theory:
S. Tchoumakov[1], M. Goerbig[1], D. Carpentier[2],
1 : Laboratoire Physique des Solides, U-Psud, Orsay, France,
2 : Laboratoire Physique, ENS-Lyon, France,

Sample fabrication and magneto-transport:
K. Bendias, D. Mahler, R. Schlereth, E. Bocquillon, C. Brüne, H. Buhmann, L.W. Molenkamp,
Universität Würzburg, Germany

RF field effect capacitor (B=0)



Motivation

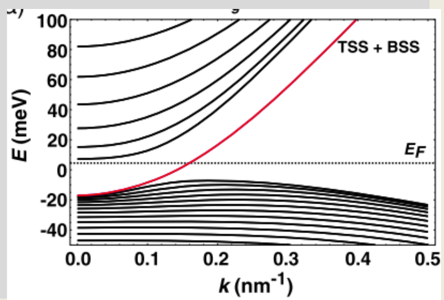
Mercury telluride (HgTe)

MBE growth
→ Batch processing

High quality
→ Mobilities ~10^5 $cm^2/(Vs)$

Negligible bulk doping

Small (bulk) gap:
25meV



„Topological surface state screening“

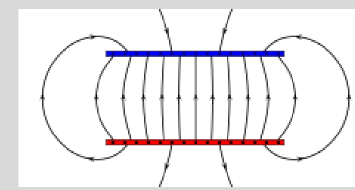
PHYSICAL REVIEW X 4, 041045 (2014)

Dirac-Screening Stabilized Surface-State Transport in a Topological Insulator

Christoph Brüne,[1] Cornelius Thienel,[1] Michael Stuiber,[1] Jan Böttcher,[2] Hartmut Buhmann,[1] Elena G. Novik,[1] Chao-Xing Liu,[3] Ewelina M. Hankiewicz,[2] and Laurens W. Molenkamp[1]

“[…]These observations imply that even at large carrier densities, the transport is surface-state dominated, where bulk transport would have been expected to coexist already.[…]”

Screening?
→ (critical) electric field
→ Capacitor!



Compressibility

μ: chemical potential
n: charge carrier density

Thermodynamics :

$$d\mu(n,T,E,B,\dots) = \frac{1}{\chi}dn - SdT + \widetilde{D}dE + \widetilde{H}dB + \cdots$$

Compressibility : $\chi(n,T,E,B,\dots) = \left(\frac{\partial n}{\partial \mu}\right)_{T,E,B=cte} = DoS(\varepsilon_F, E, B, T)$

Outline

Introduction: Concepts and experimental principles

Results: Low and high frequency compressibility

Model: Massive surface states

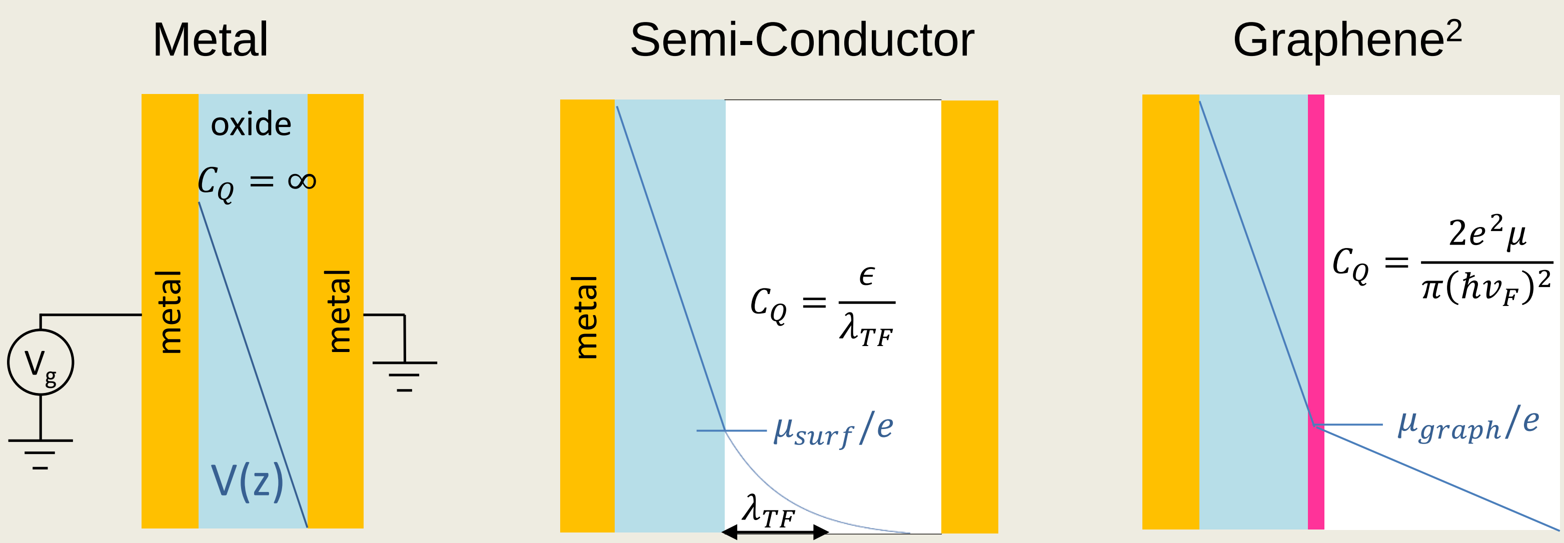
Compressibility and quantum capacitance

Compressibility : $\chi(n,T,E,B,\dots) = \left(\frac{\partial n}{\partial \mu}\right)_{T,E,B=cte} = DoS(\varepsilon_F, E, B, T)$

Quantum capacitance : $\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_Q}$; $\frac{C_Q}{e^2} = \left[\frac{\partial n_{tot}}{\partial \mu_{surf}}(n,B,T,\dots.)\right]_{E=ne\epsilon_{ox}}$

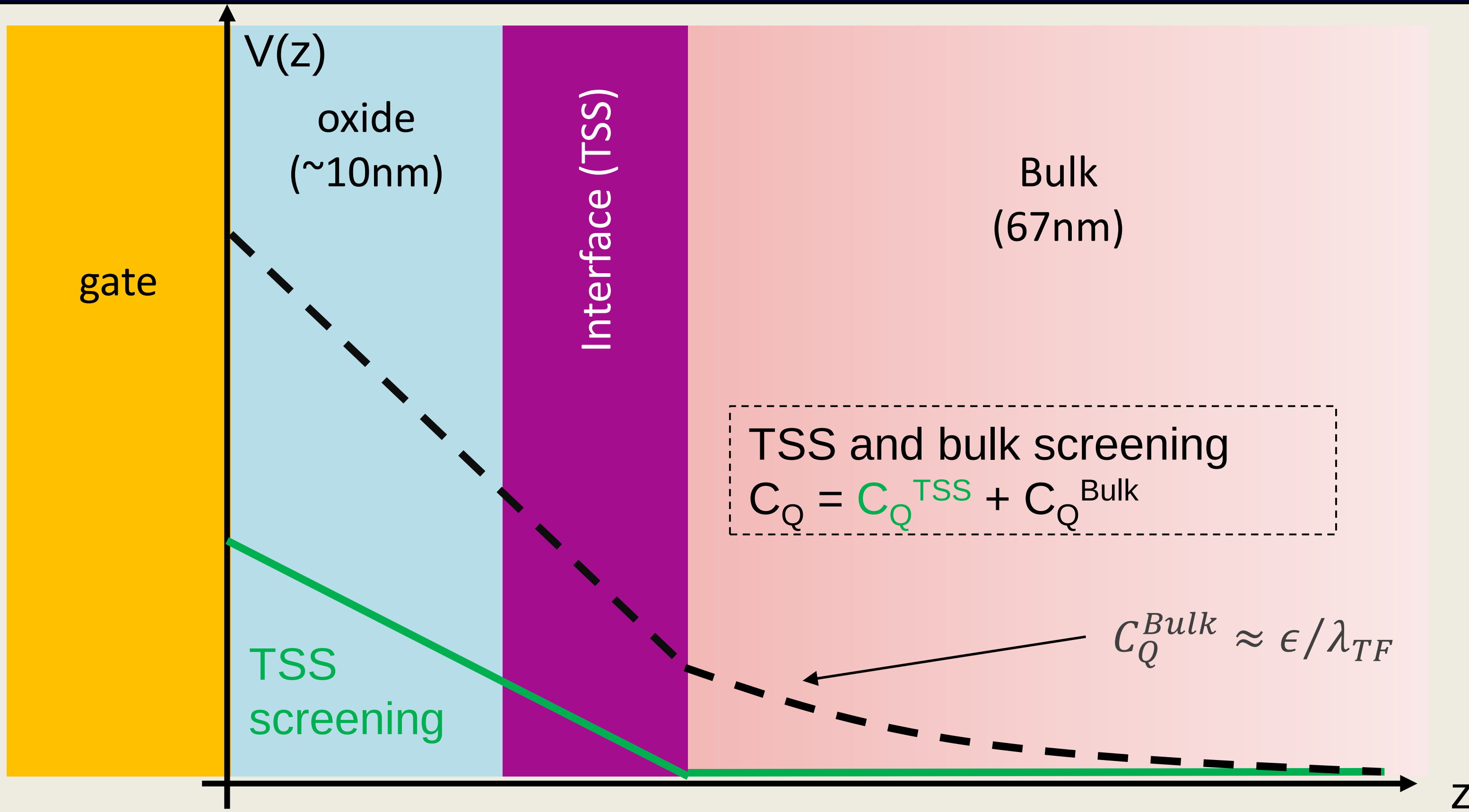
Surface chemical potential[1] : $\mu_{surf} = \int \frac{\partial \mu_{Surf}}{\partial n_{tot}} dn = e\int_{V_{DP}}^{V_g} \frac{C(V)}{C_Q(V)}\, dV$

μ: chemical potential
n: charge carrier density



1) *Berglund, IEEE TED (1966)*
2) *Graphene compressibility : E Pallecchi et al., PRB 83, 125408 (2011)*
See also HgTe magneto-compressibility by D. A. Kozlov et al., PRL 116, 166802 (2016)

TI Field Effect Capacitor

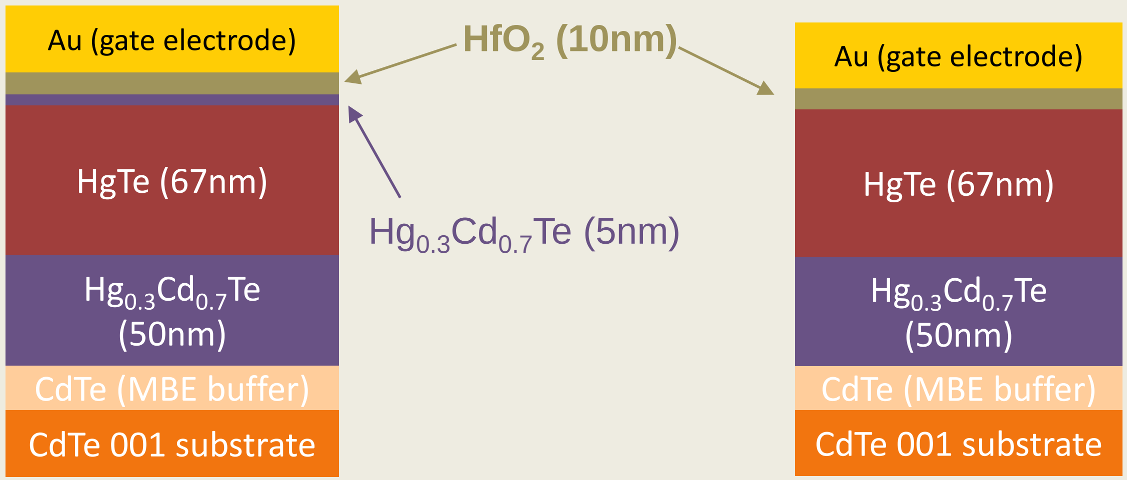


- Investigate equilibrium properties of Topological Matter : $\mu(n, E, T, B, \dots)$
- Limit of TSS screening → Critical electrical field E_c
- Understand interplay between TSS and BS screening
- RF capacitor: acces dynamical properties of TSSs : diffusion constant $\mathrm{D}(n, E, T, B, \dots)$

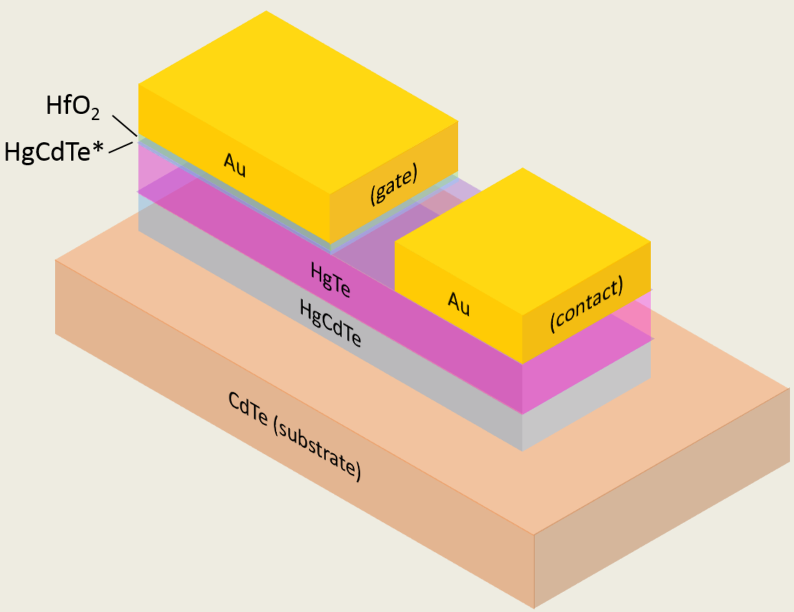
HgTe RF field effect capacitor

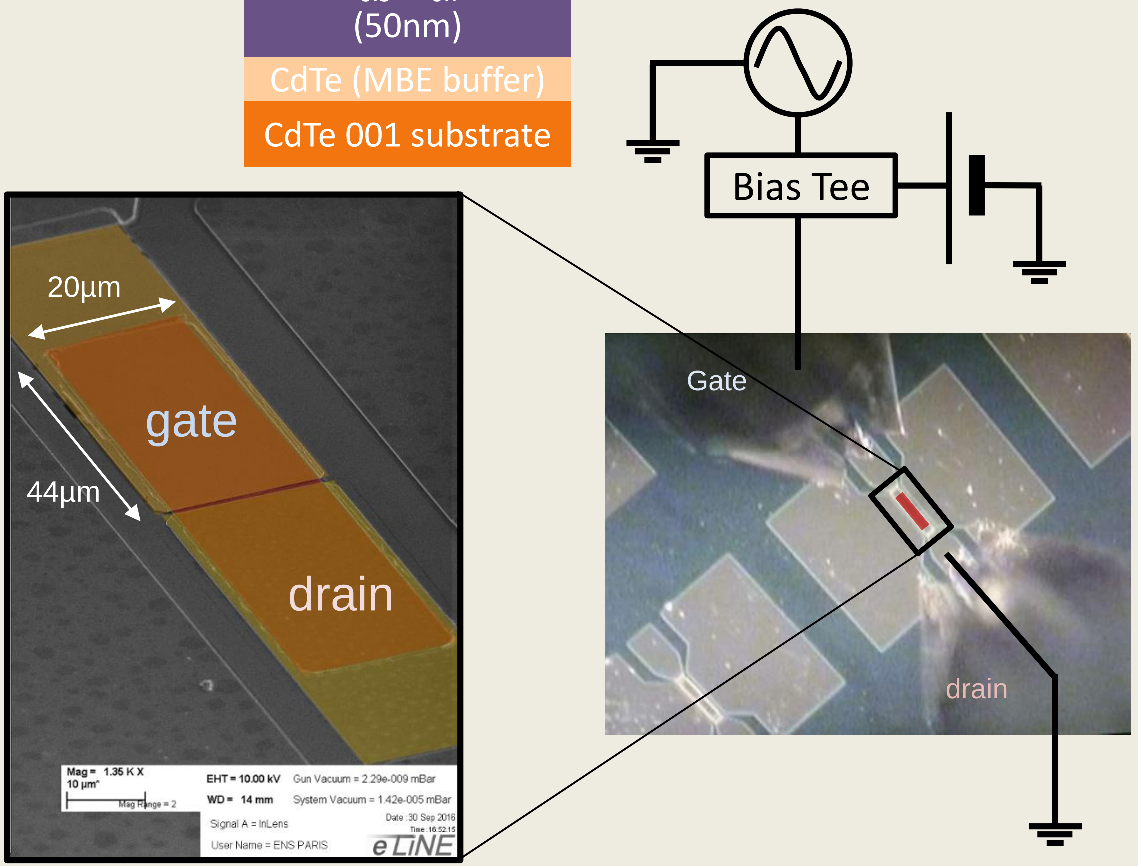
Capped sample ($< 2 \cdot 10^{16} cm^{-3}$) | No capping (doping $\sim 4 \cdot 10^{17} cm^{-3}$)

Doping $\leq 2\ 10^{16} cm^{-3}$
Mobility $\approx 10^{5} cm^{2}/Vs.$



Doping $\approx 4\ 10^{17} cm^{-3}$
Mobility $\approx 10^{4} cm^{2}/Vs.$





Sample fabrication: Molenkamp group in Würzburg

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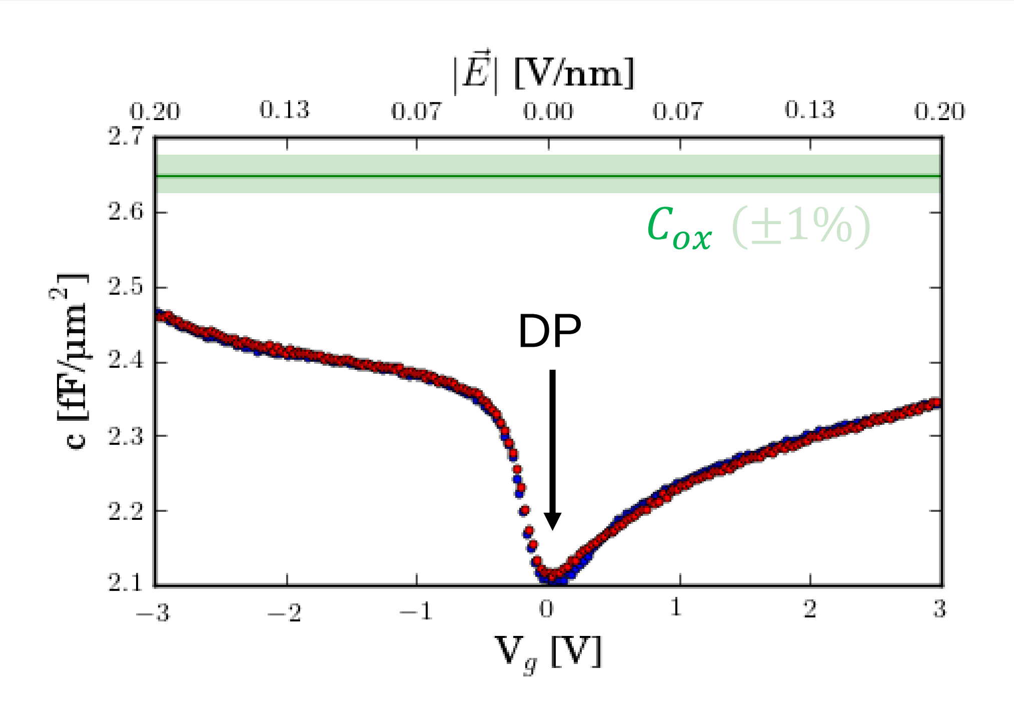
Results: Low and high frequency compressibility

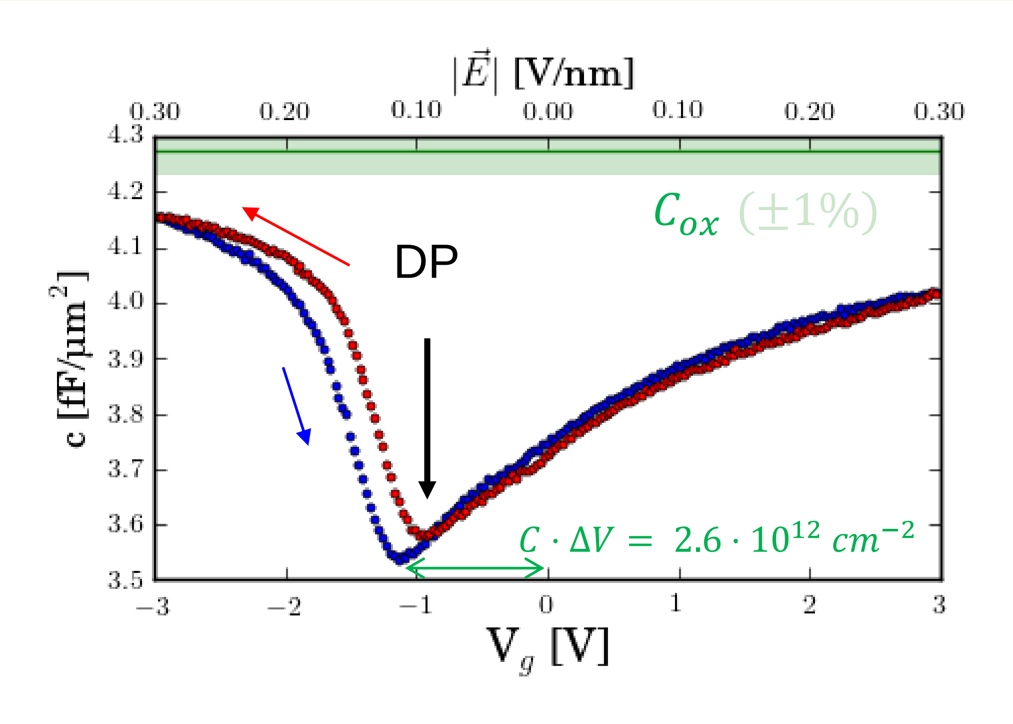
Model: Massive surface states

Quasi-static Lock-in measurements (10kHz)

capped (undoped)



uncapped (doping $\approx 4 \cdot 10^{17}\ cm^{-3}$)

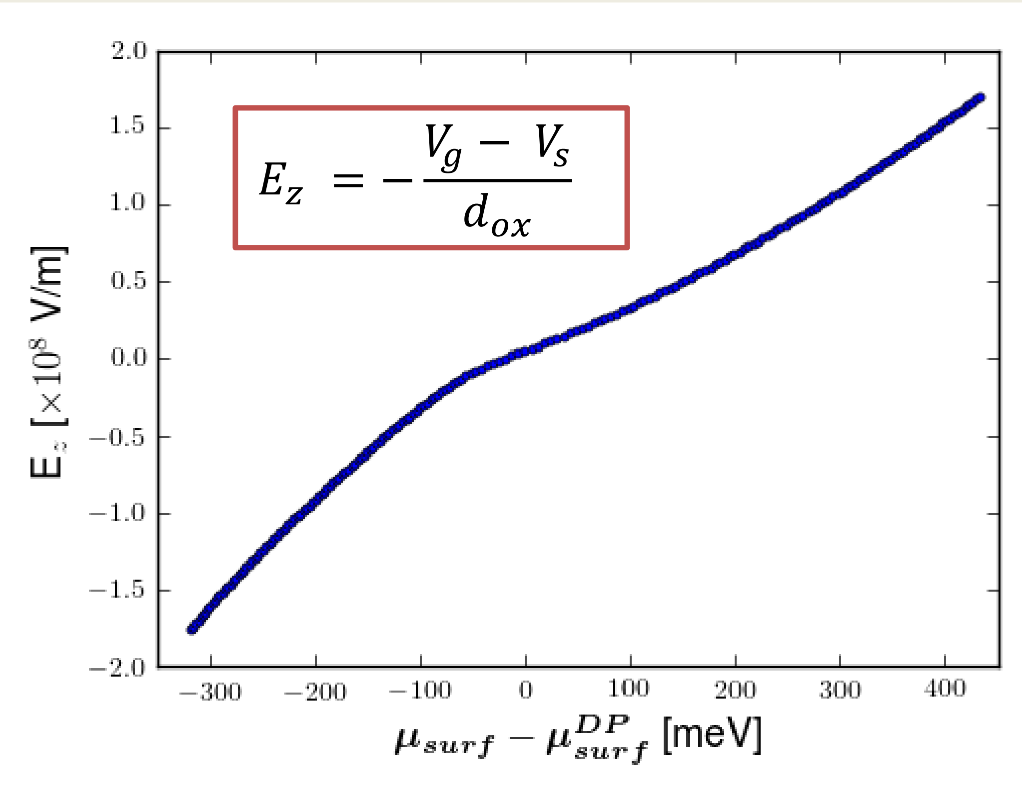


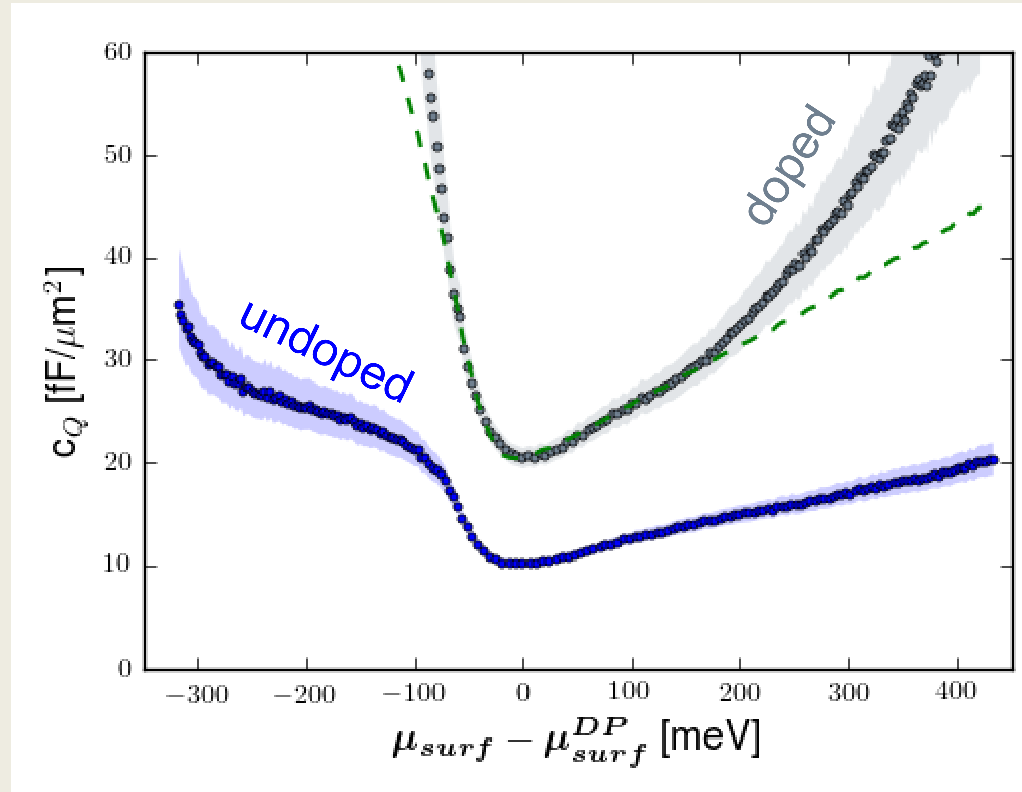
- Reversible capacitance
- Minimum indicates BG / DP position ($\pm 6\ meV$) and doping
- Capped is « undoped »; uncapped sample is electron doped at $4 \cdot 10^{17}\ cm^{-3}$

Analysis…

$$\frac{1}{C_Q} = \frac{1}{C} - \frac{1}{C_{ox}}$$

$$\mu_{surf} = \int \frac{\partial \mu_{Surf}}{\partial n_{tot}} dn = e \int_{V_{DP}}^{V_g} \frac{C(V)}{C_Q(V)} dV$$



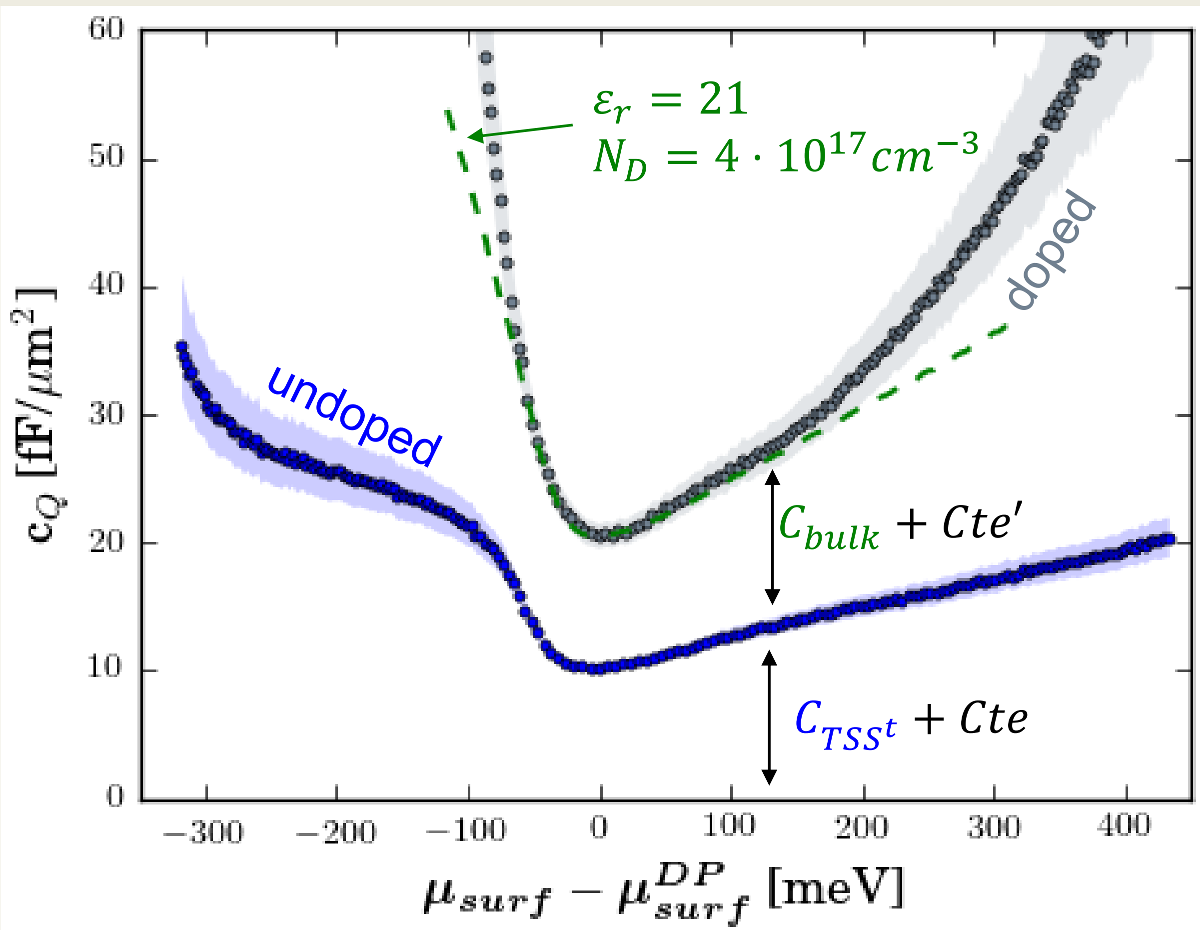


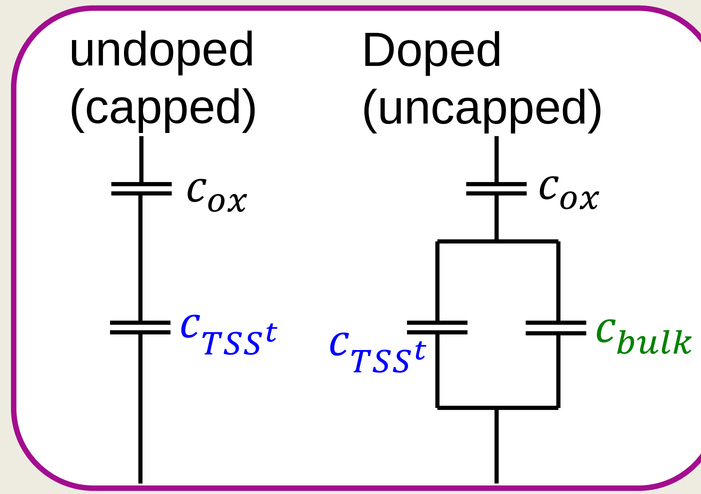
- Quantitative determination of c_Q, μ_s and E_z
- Variation of μ and E_z over very large ranges: μ~400meV, E_z~2x10^8V/m

Thomas-Fermi compressibility of Bulk States

$$\frac{1}{C_Q} = \frac{1}{C} - \frac{1}{C_{ox}}$$

$$\mu_{surf}(V_g) = e\int_{V_{DP}}^{V_g}\left(1 - \frac{C}{C_{ox}}\right) dV$$



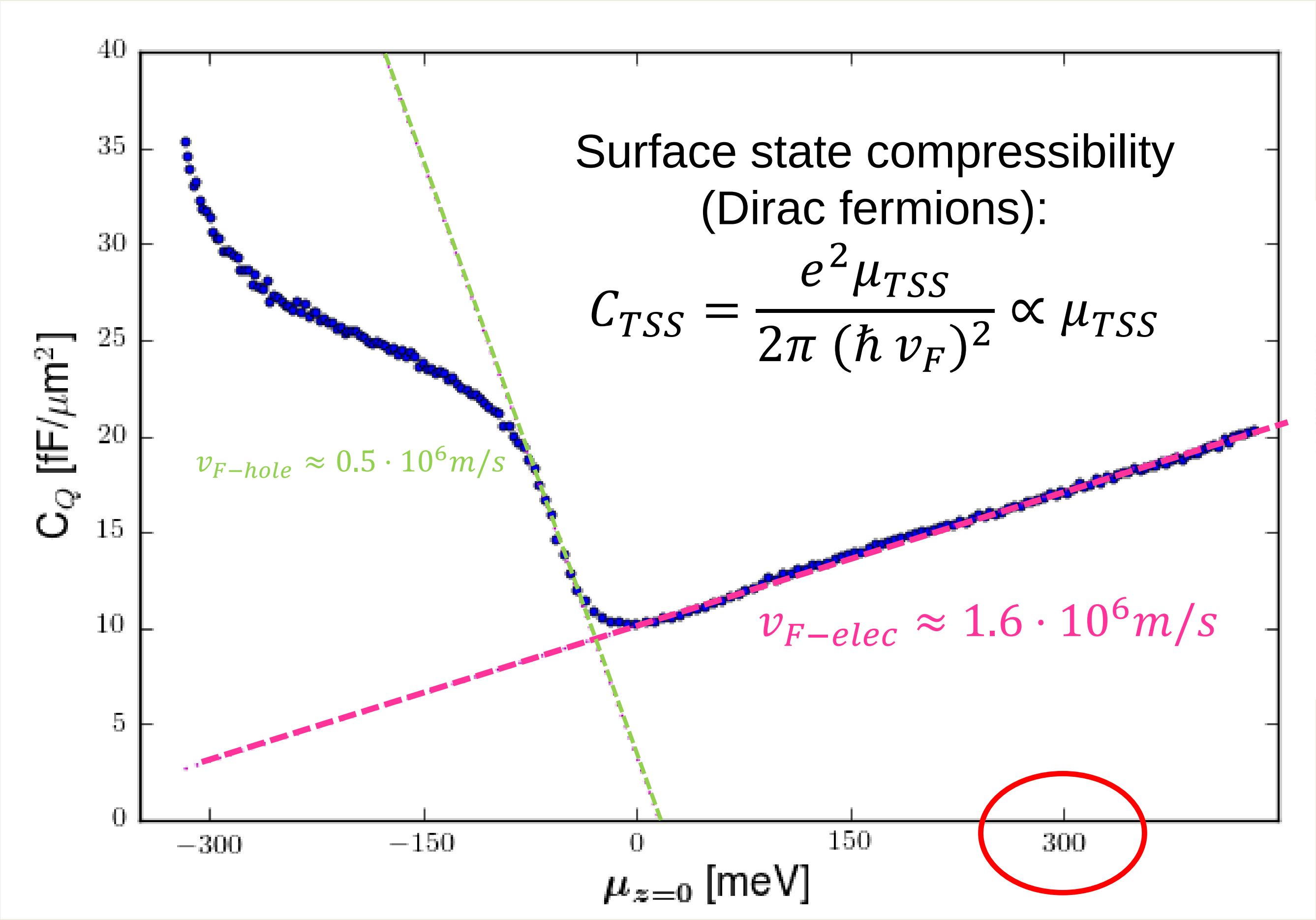


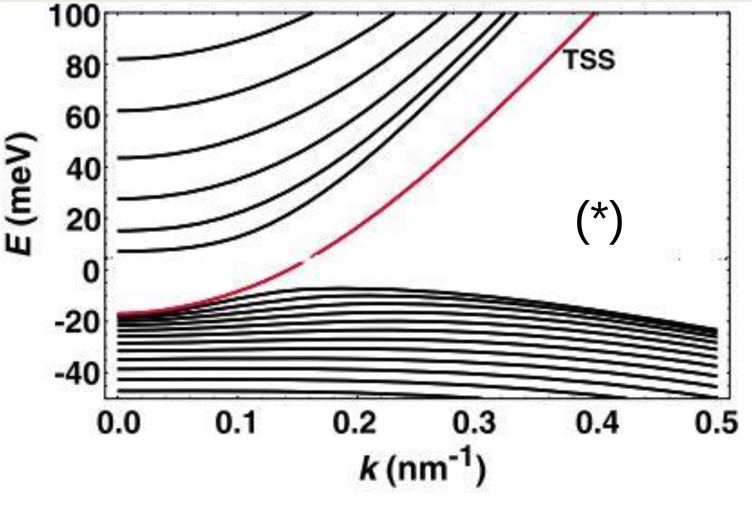
Formula for bulk compressibility :

$$C_{bulk} = \frac{\epsilon}{\lambda_{TF}(V_0)} = \sqrt{\frac{e\epsilon}{2}}\frac{N_D - N(\mu_\infty + eV_0)}{\sqrt{\int_{V_0}^{0} dV[N_D - N(\mu_\infty + eV)]}}$$

- Difference between doped and undoped explained by TF screening in the bulk ($\lambda_{TF} \approx 6\,nm$)
- Small backgroung signal also for undoped sample (background $\Leftrightarrow N_D < 2 \cdot 10^{16} cm^{-3}$)

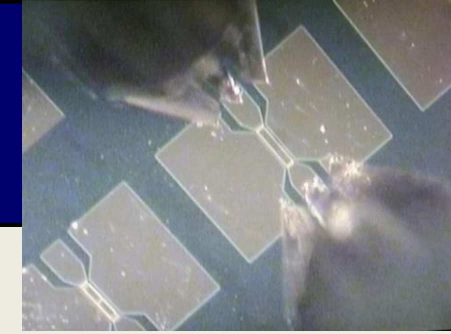
TSS compressibility



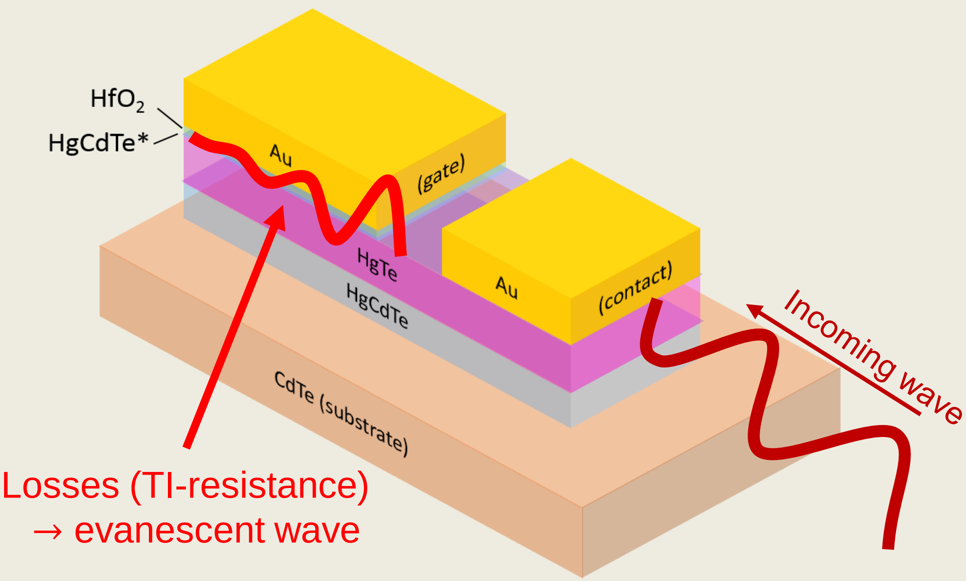


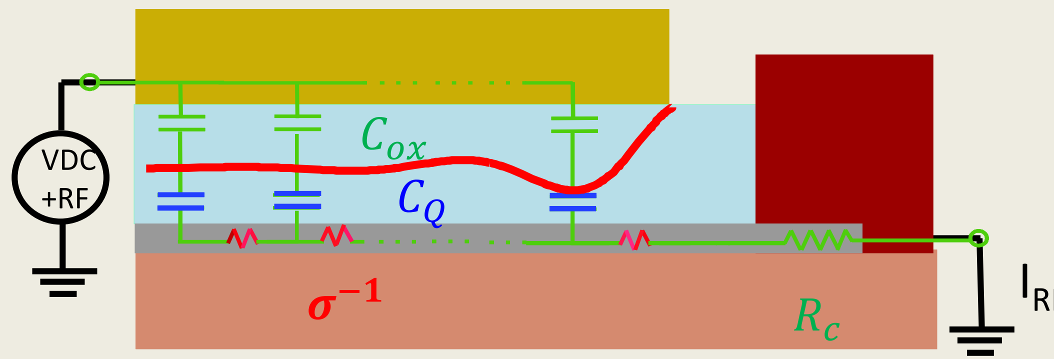
- Pure TSS compressibility (no bulk contribution) up to μ_{surf} >300 meV (>> **Δ**=30meV)
- TSS screening over 300meV (>> **Δ**=30meV) *c.f.* (*) C. Brüne *et al,* PRX 4, 041045 (2014)

From DC to RF Capacitor



- 40 GHz Vectorial Network Analyzer
- Complex spectrum
- Broad band
- DC to evanescent wave regime





<u>Capacitor's complex admittance spectrum</u>

- Simple sample geometry → 1D model:

$$Y = j\omega C L W \times \frac{\tanh\left(L\sqrt{jC\omega/\sigma}\right)}{L\sqrt{jC\omega/\sigma}}$$

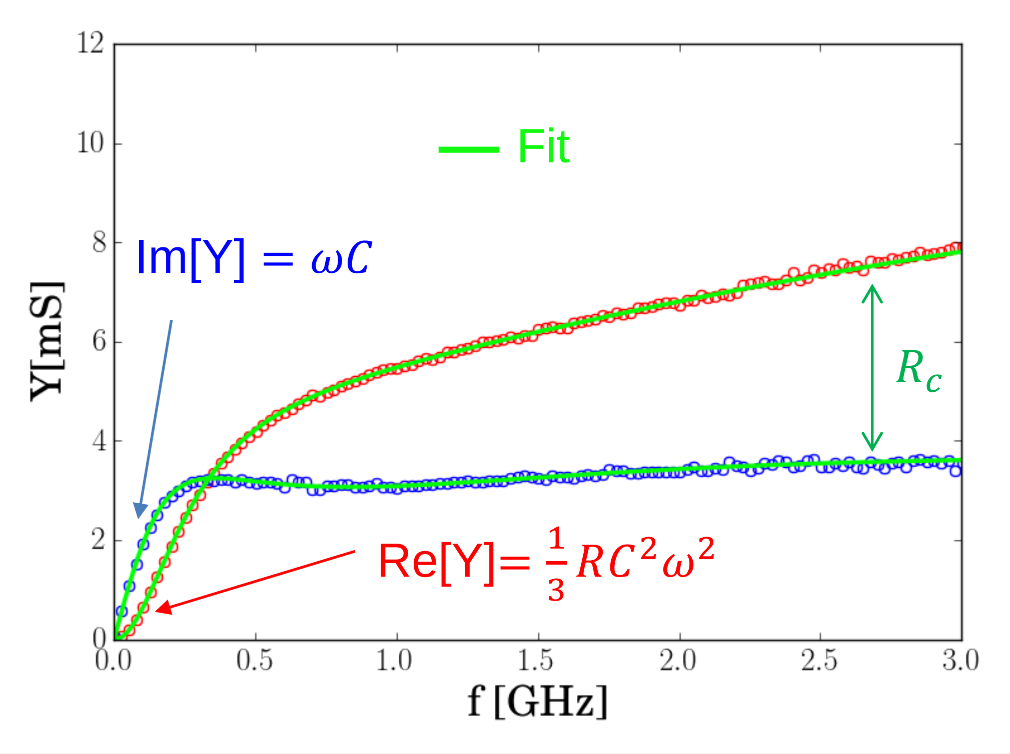
- capacitance C + conductivity σ

<u>Einstein-Boltzmann relation</u>

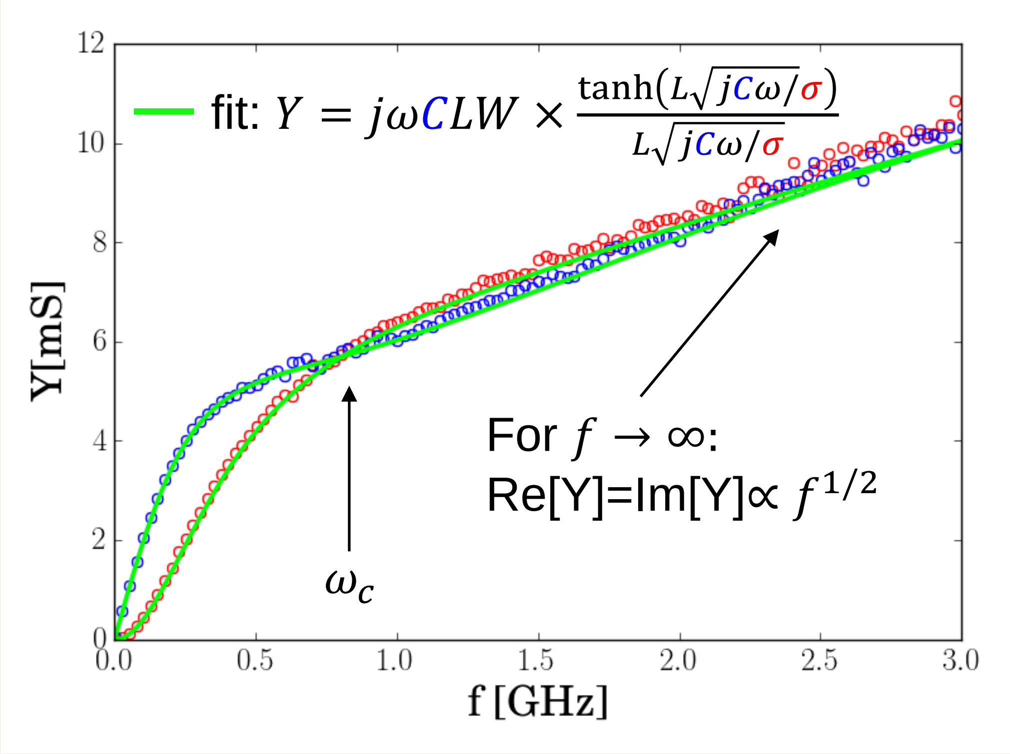
$$\sigma_{xx}(\mu) = C_Q(\mu) \cdot D(\mu)$$

RF Admittance spectrum

Raw admittance spectrum

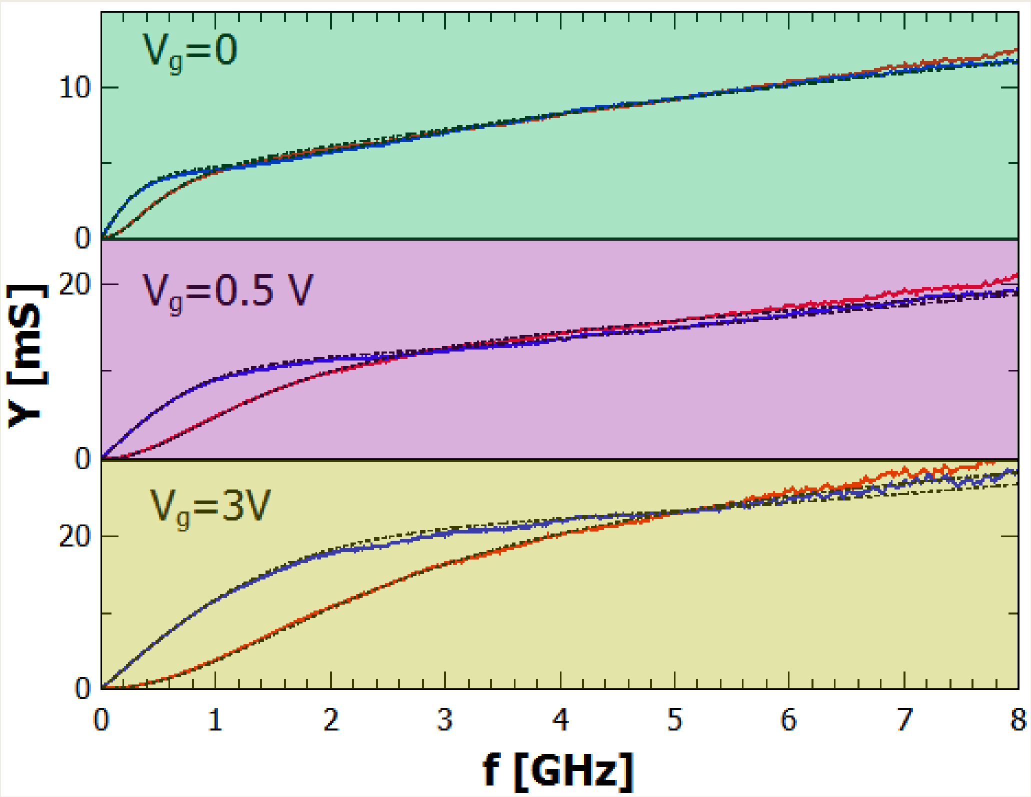


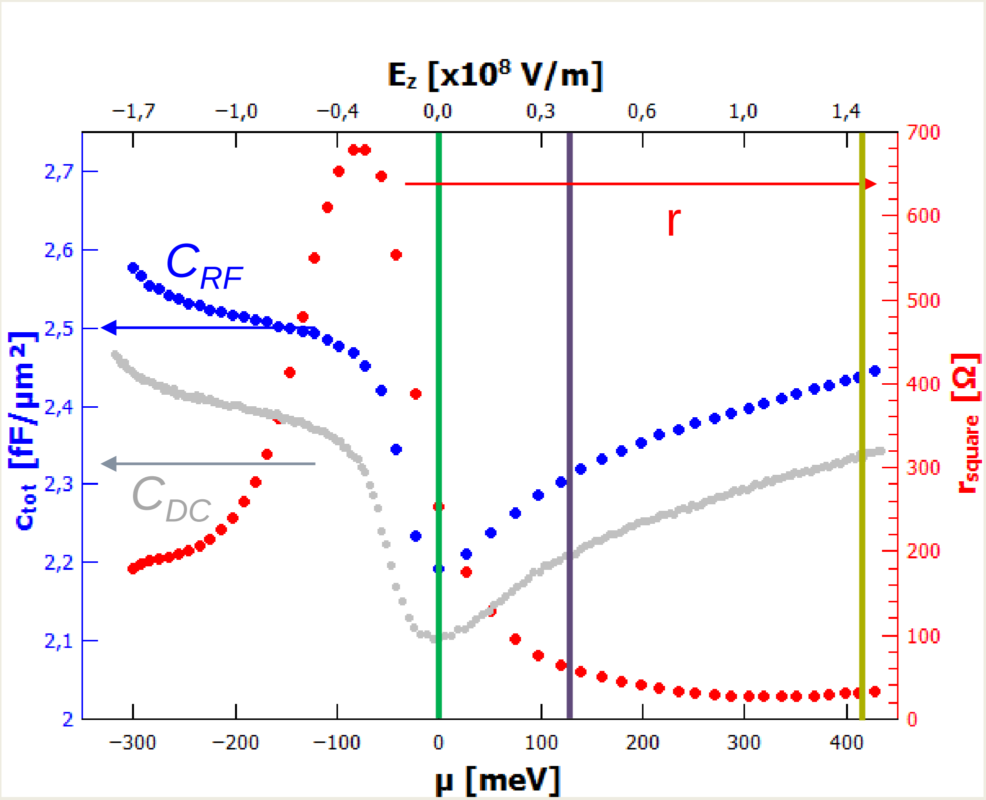
Corrected for contact resistance (~1.6 kΩ ·μm)



- Crossing corresponds to $RC\omega_c \sim 1$
- Evanescent waves at high frequency $\mathrm{Re}[Y] = \mathrm{Im}[Y] \propto f^{1/2}$
- 3-parameter fit → total capacitance C, conductance σ and contact resistance R_c

Gate dependent admittance spectra

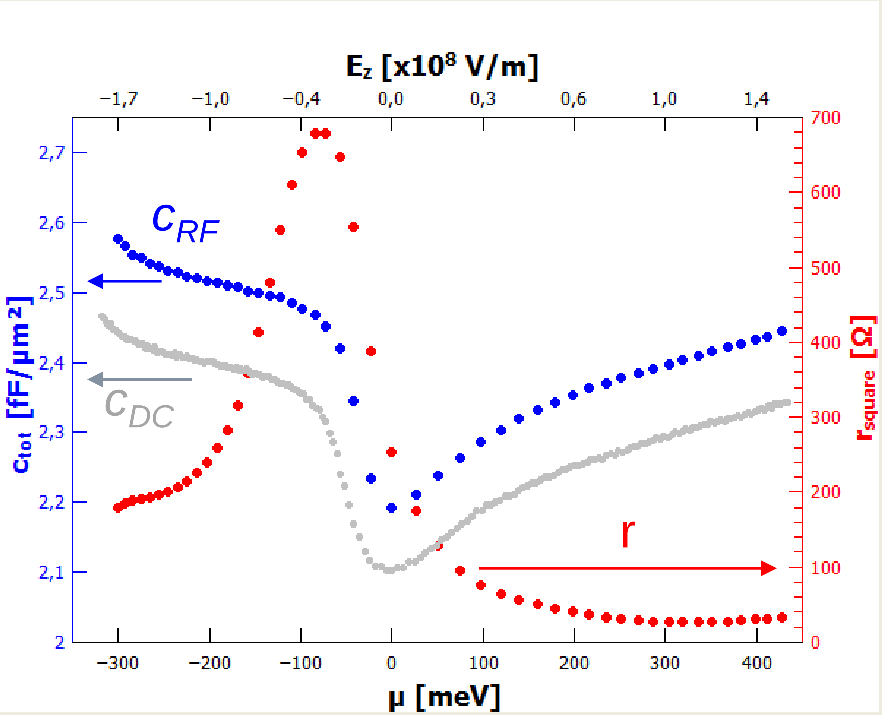




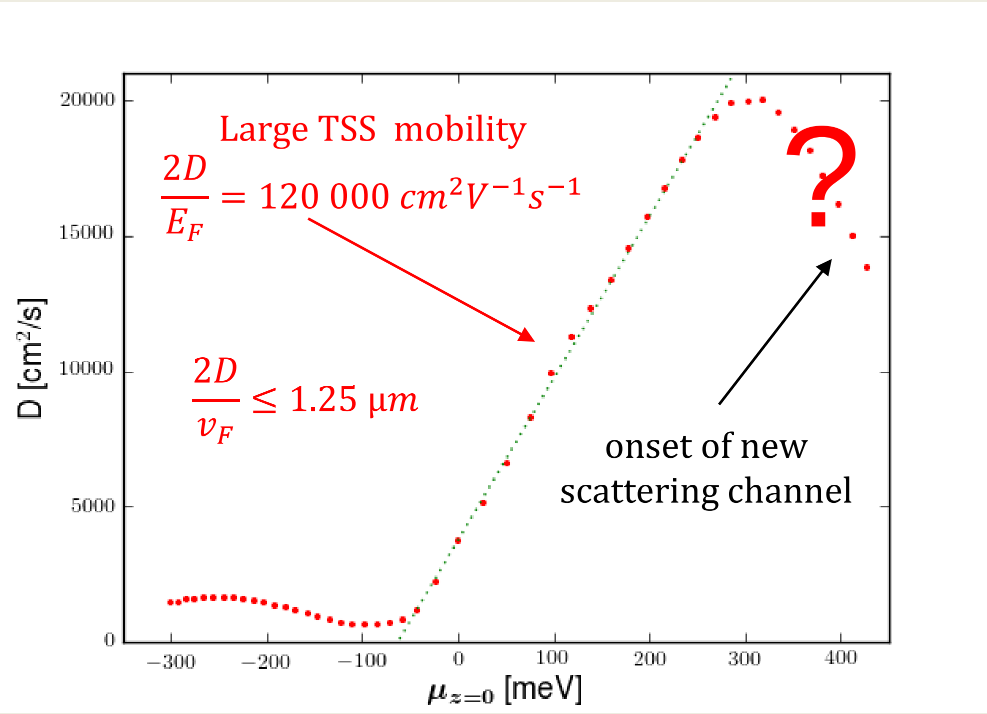
- ➢ 1D model remains valid for all gate voltages
- ➢ $C_{RF} \approx C_{quasi\text{-}DC}$ (difference due to amplifier offset)
- ➢ Additional information from resistance

Reversible RF compressibility

TSS Capacitance/Conductivity



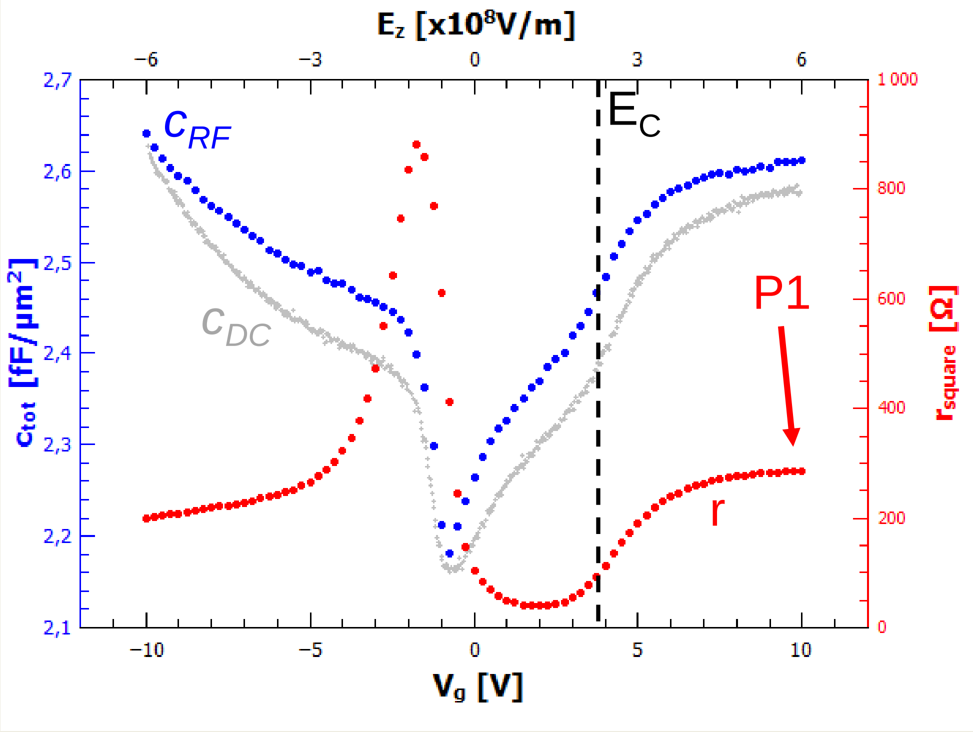
Diffusion Constant $D = \frac{1}{r c_Q}$



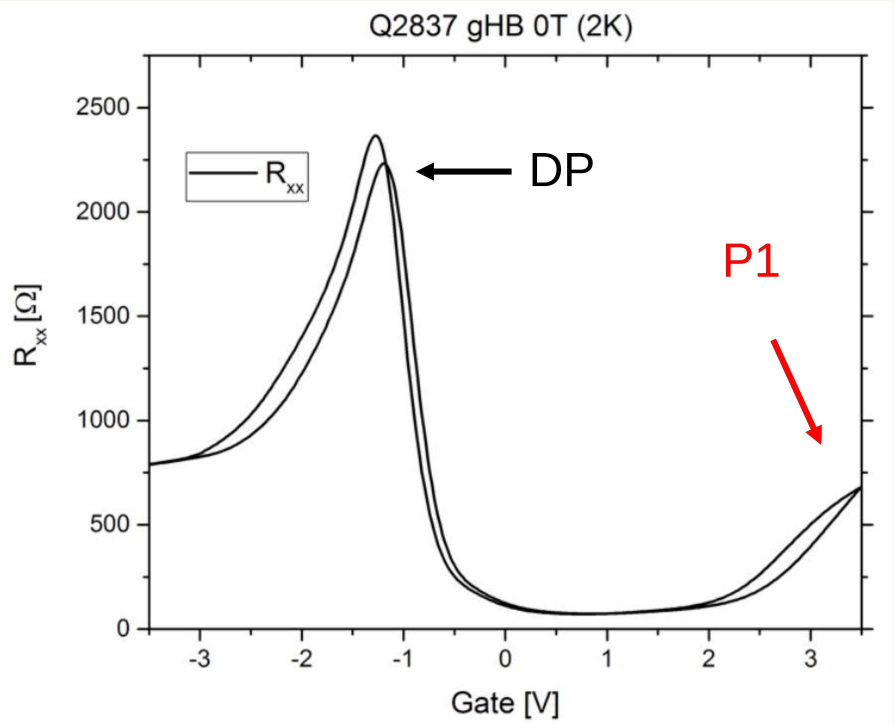
- RF and DC capacitance almost coïncide (blue and grey)
- Asymetric conductance for electrons and holes (red)
- Linear $D(\mu) \rightarrow$ large TSS mobility ($\mu \approx 120\,000\ cm^2V^{-1}s^{-1}$)
- Fingerprint of a new scattering mechanism above $300\ meV$

Broad electric field range : undoped sample

RF capacitor (Paris)



Hall-bar (Würzburg)



- Onset of new scattering develops into a resistance peak at large electric field
- Also seen in the Hall bar
- Resistance peak is accompanied by a capacitance shoulder

Experimental observations

- ~20% Capacitance variation → quantitative analysis of c_Q
- Batch- but not sample-dependent results!
- TSS screening over large range of μ (>10x gap) and large electric fields (~10^8V/m).
- Shoulder in capacitance and resistance peak → Critical field:

$$E_c \approx 2.2 \times 10^8 \text{V/m}$$

Outline

Introduction: Concepts and experimental principles

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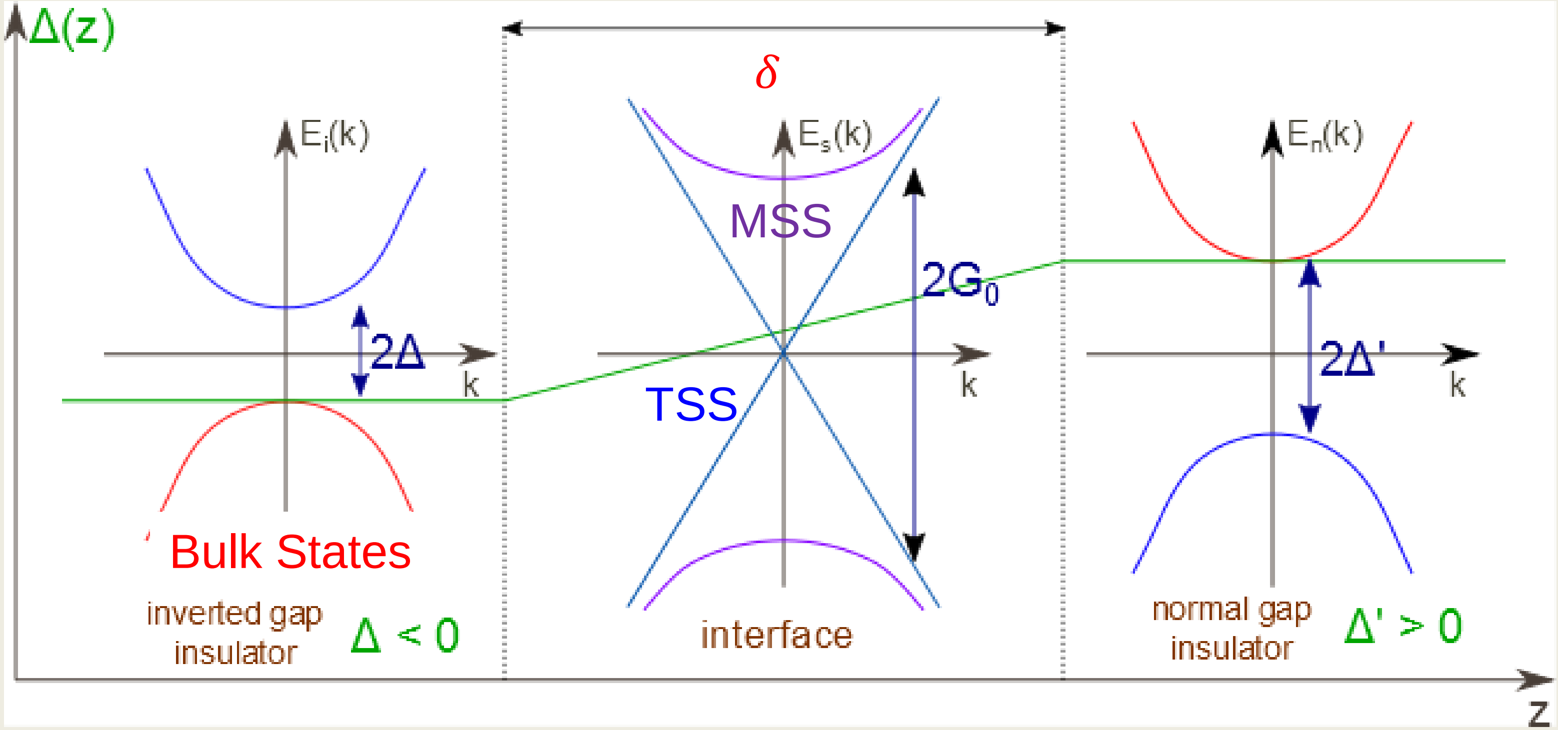
Theory : excited Massive Surface States (MSS)

- Excited surface states described by massive Dirac Hamiltonians

TI-bulk TI-surface Normal insulator



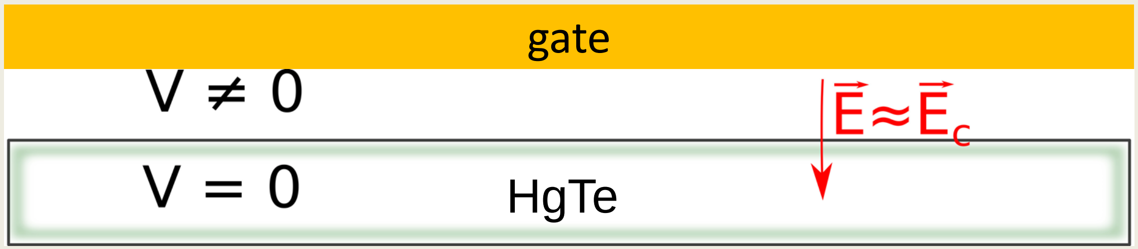
- Surface states are solutions of a 1D Dirac oscillator, with gaps

$$G_0^{(n)} = \sqrt{\frac{2(\Delta+\Delta')\hbar v_F}{\delta}}\sqrt{n} \gg \Delta, \mu, k_B T$$

Theory : S. Tchoumakov, M.O. Goerbig + D. Carpentier

Electric field effect on TSS and MSS

Gate voltage induces large fields $\vec{E}$ at the surface, comparable to a surface critical E_c



$$E_C = \frac{\Delta + \Delta'}{e\,\delta} \sim 0.6\ V/nm$$

Electric field effect on TSS and MSS

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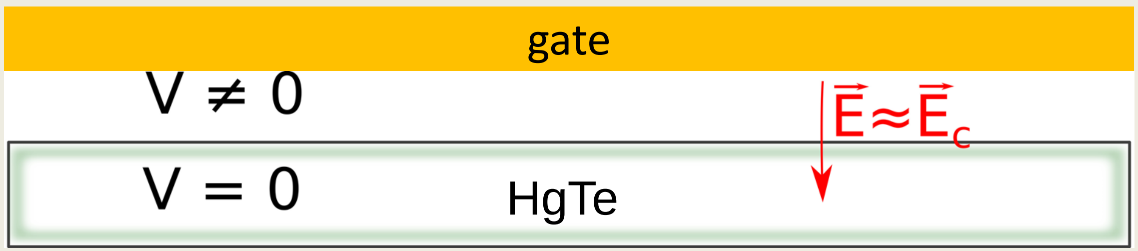

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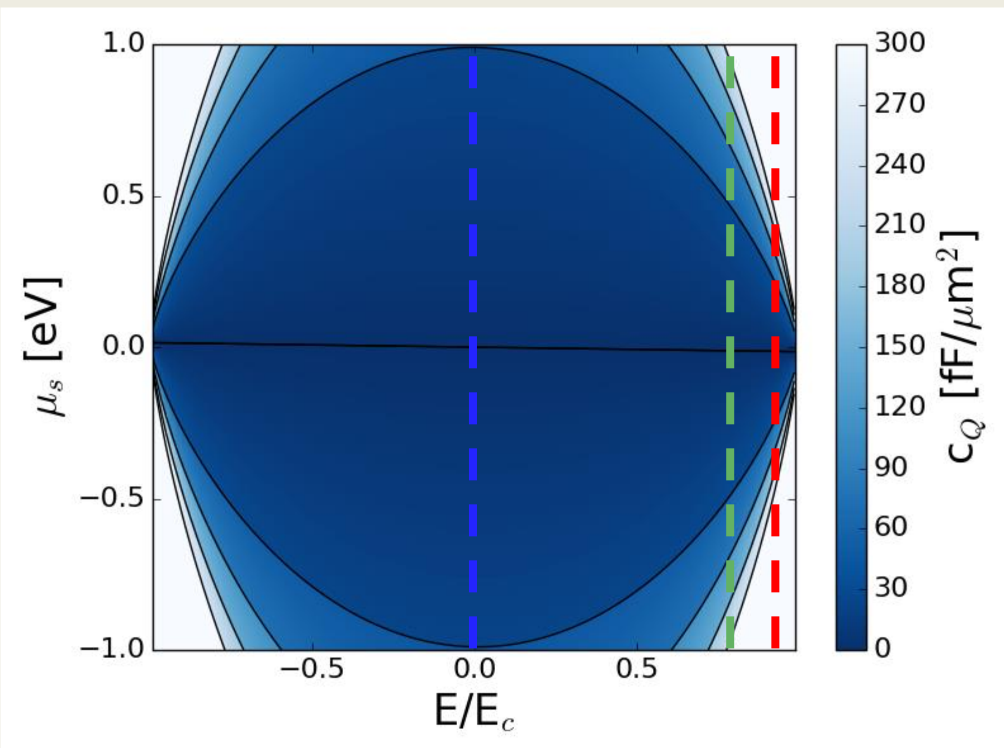

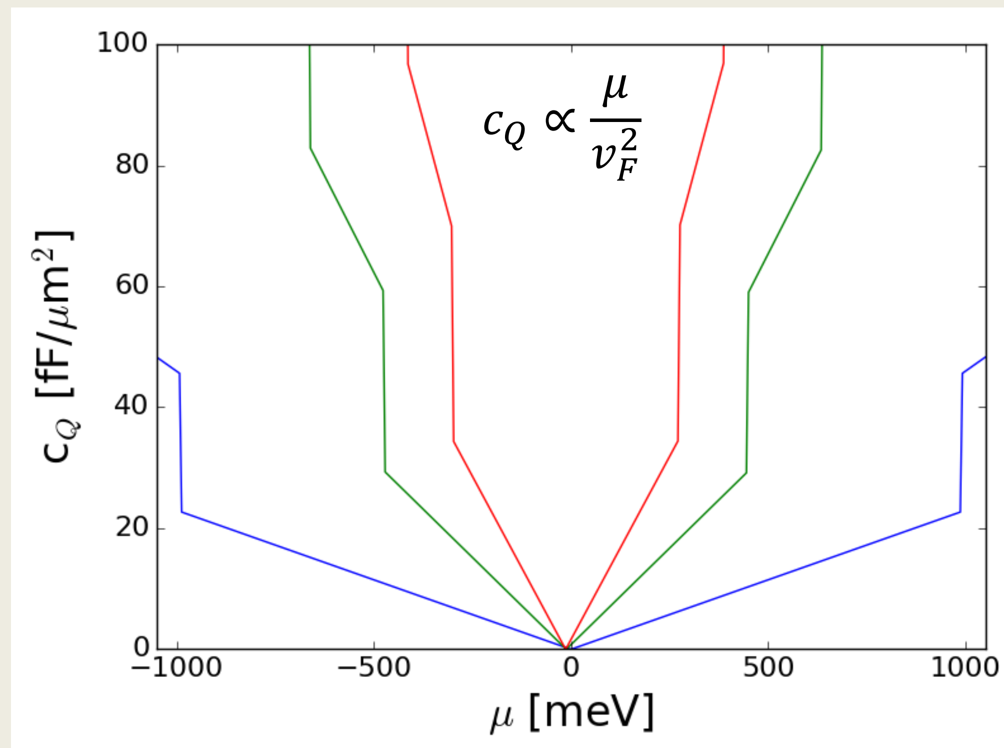

Electric field effect on TSS and MSS

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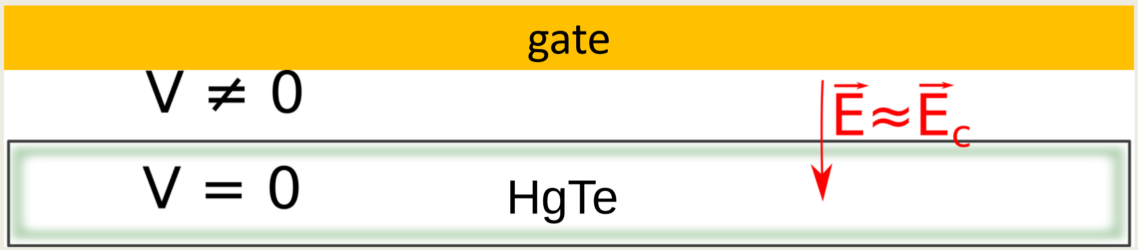
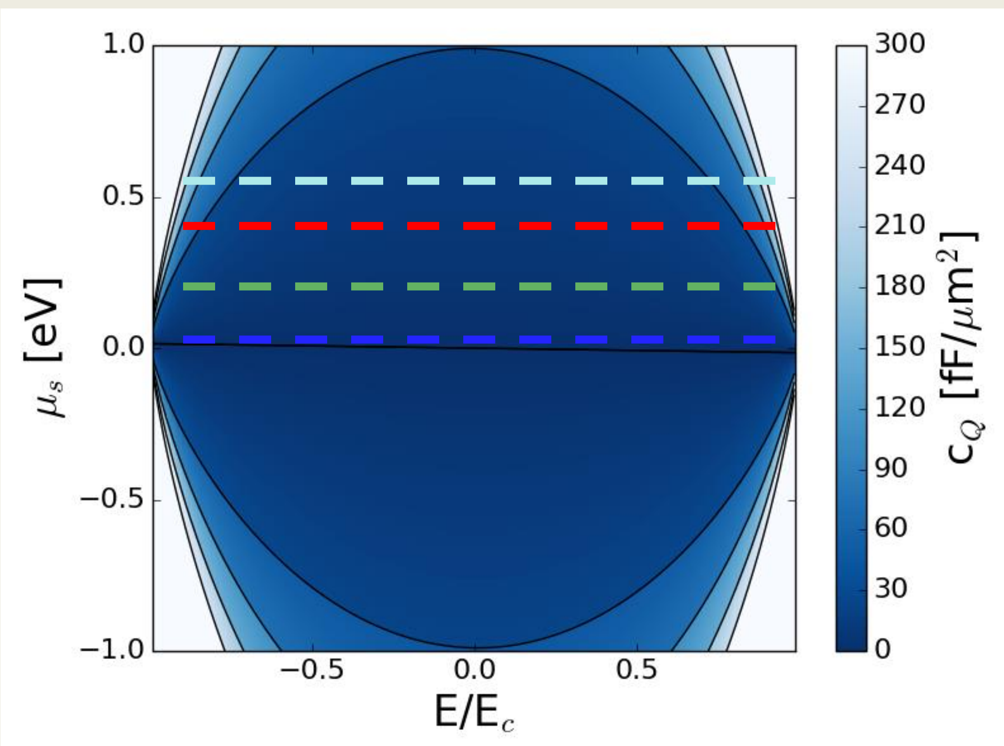
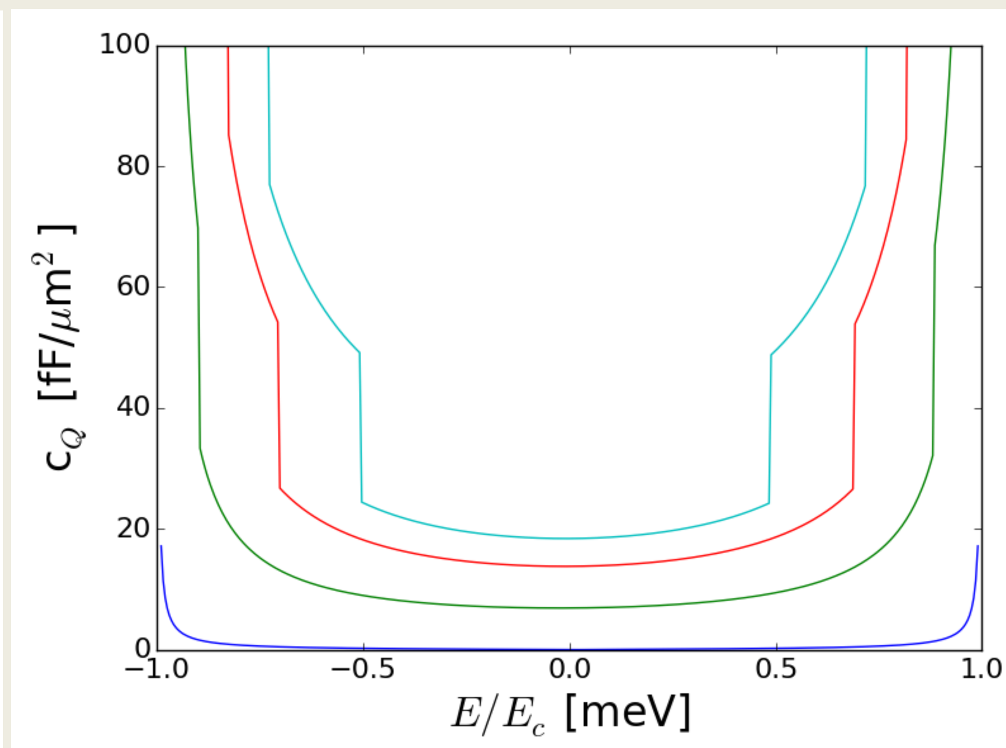


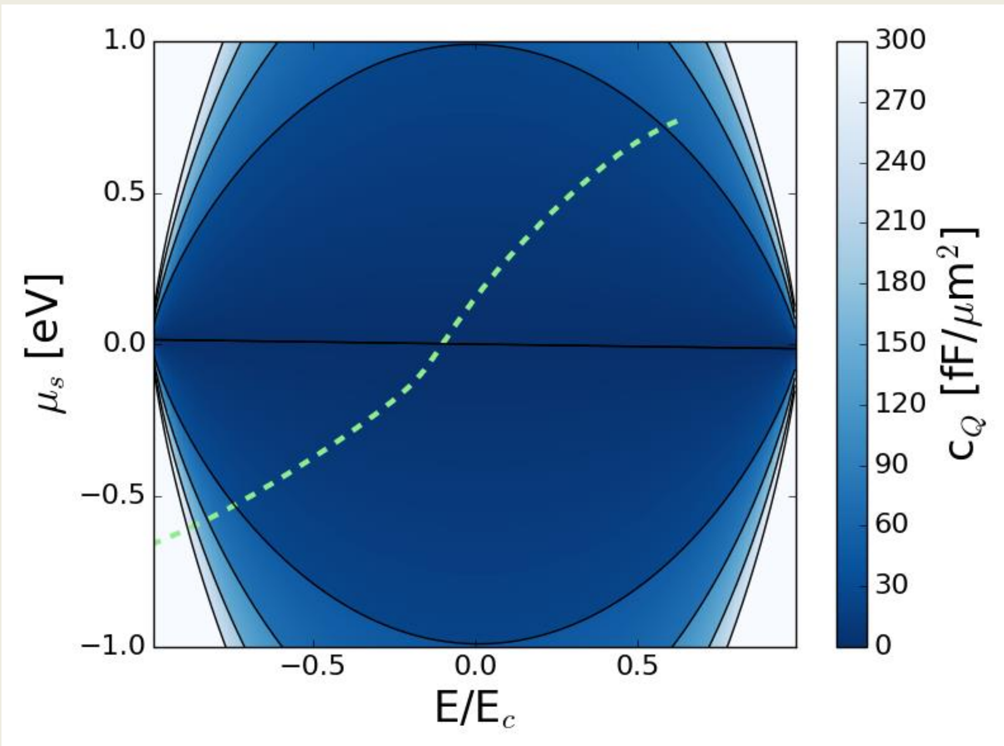
$$E_C = \frac{\Delta + \Delta'}{e\,\delta} \sim 0.6\ V/nm$$



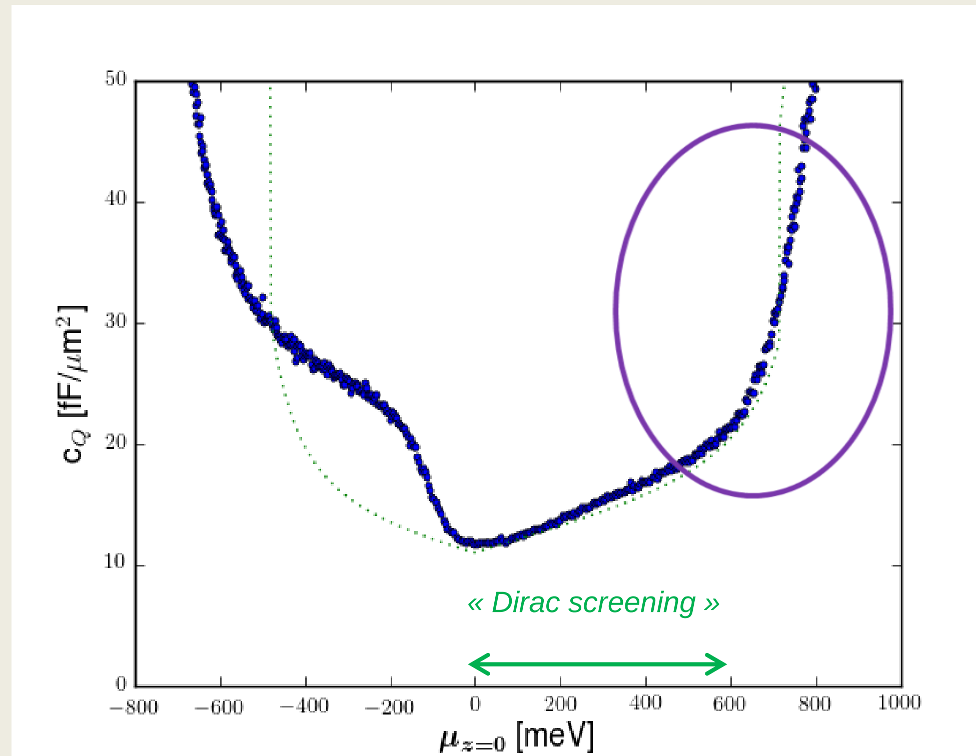


Comparison theory-experiment (undoped)

Density of states (theory)



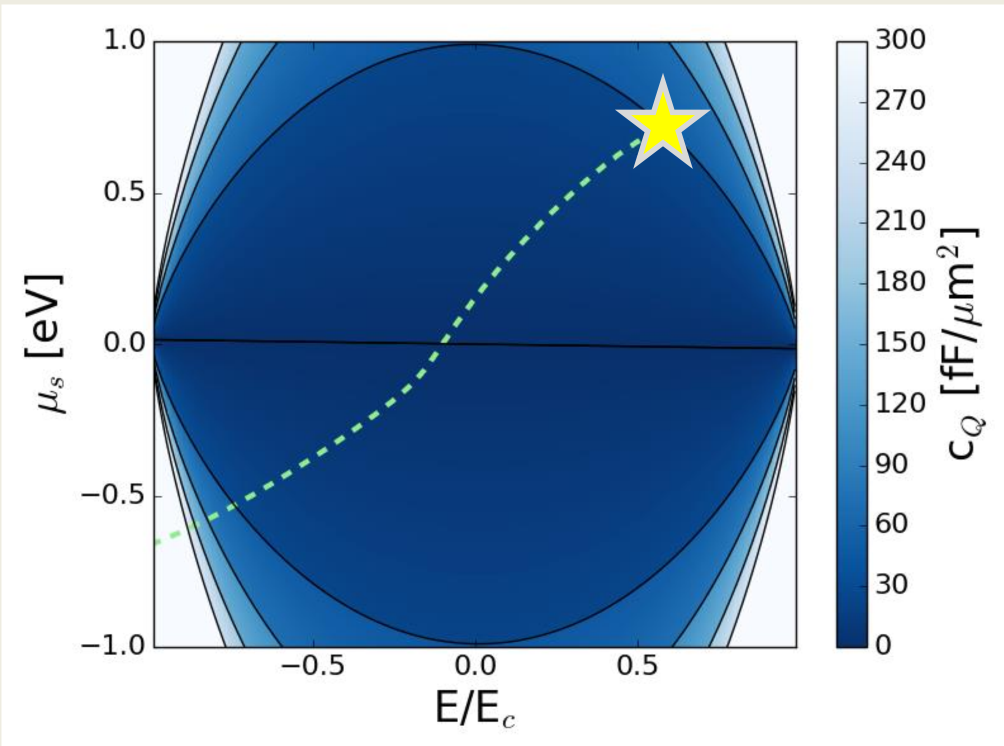
Quantum capacitance (exp.)



- Capacitance shows velocity renormalization (precursor of MSS nucleation)
- Difficult to see experimentally the capacitance step due to hysteresis
- Theoretical fit (green dotted line) with $\delta = 3nm$
- The toy model does not account for electron-hole asymetry

Comparison theory-experiment (undoped)

Density of states (theory)



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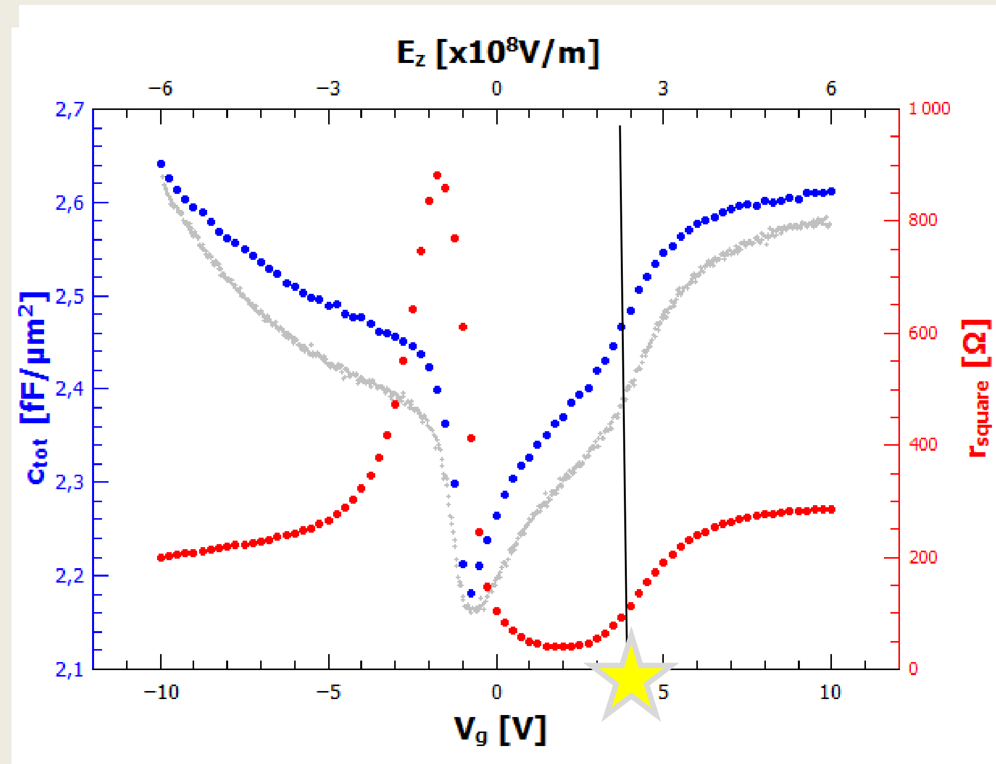
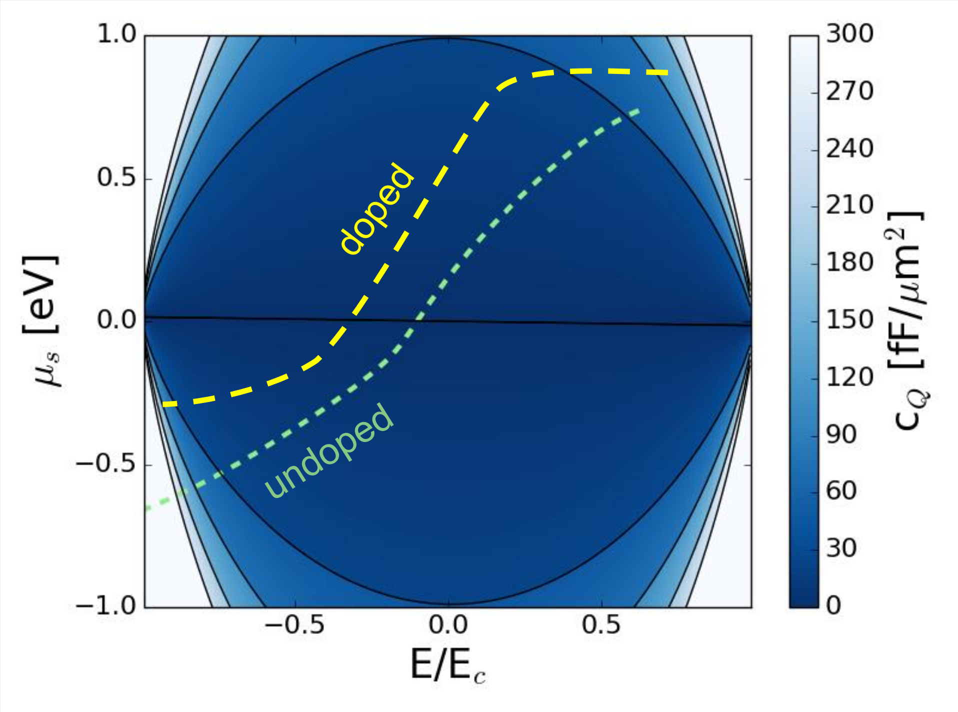
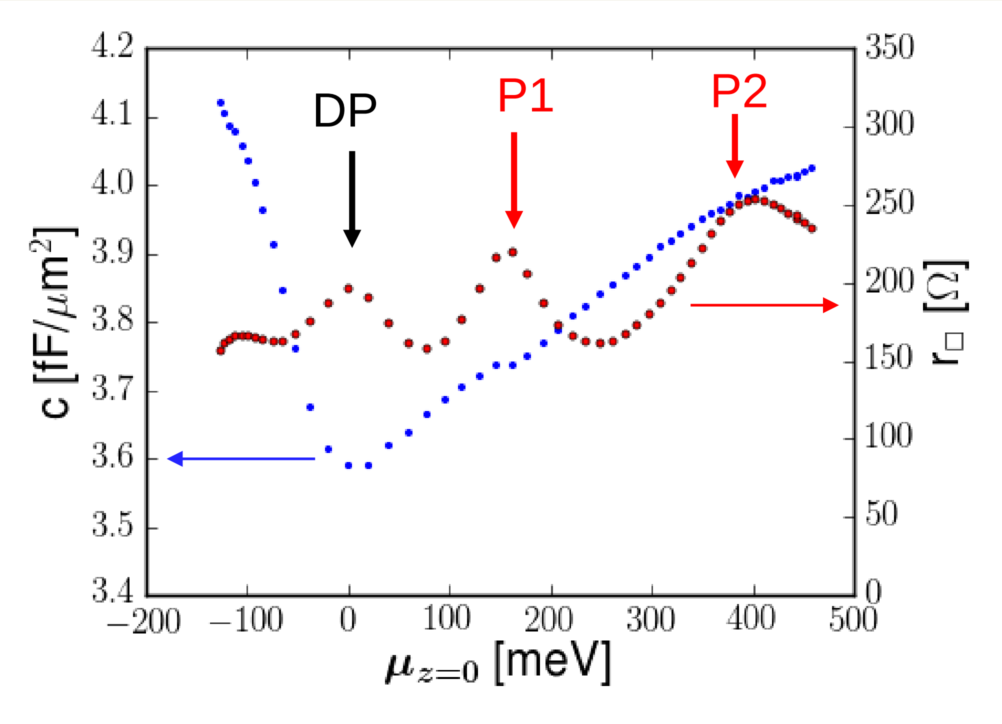


- High mobility TSS are very sensitive to scattering
- Resistance peak arises when MSS penetrates the surface (inter-subband scattering) (increased scattering DoS)

More peaks on doped sample!

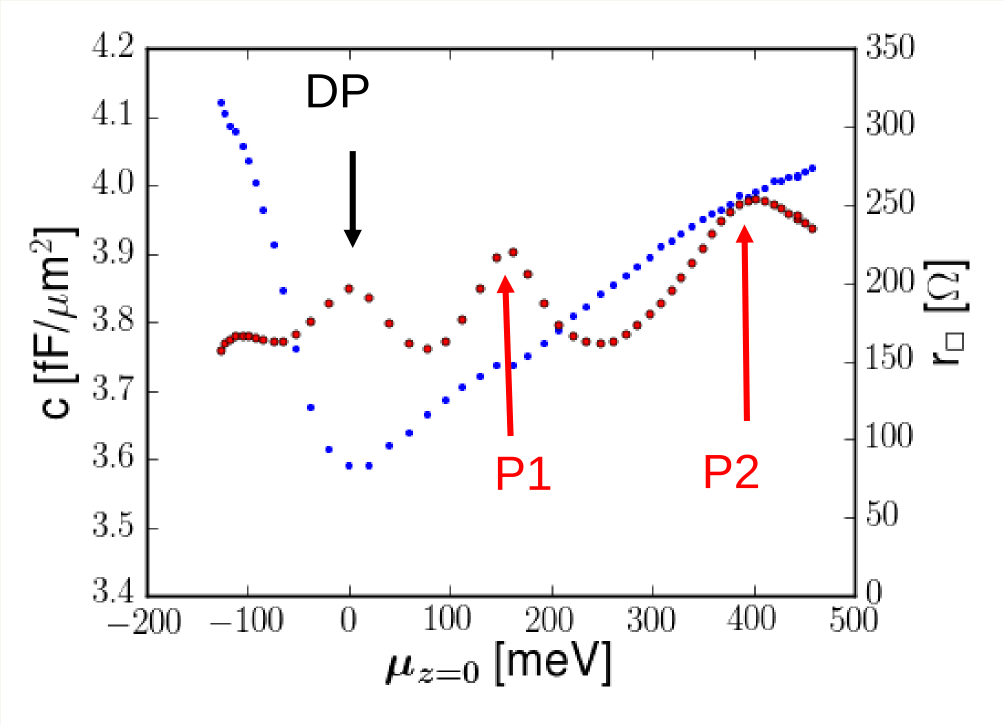




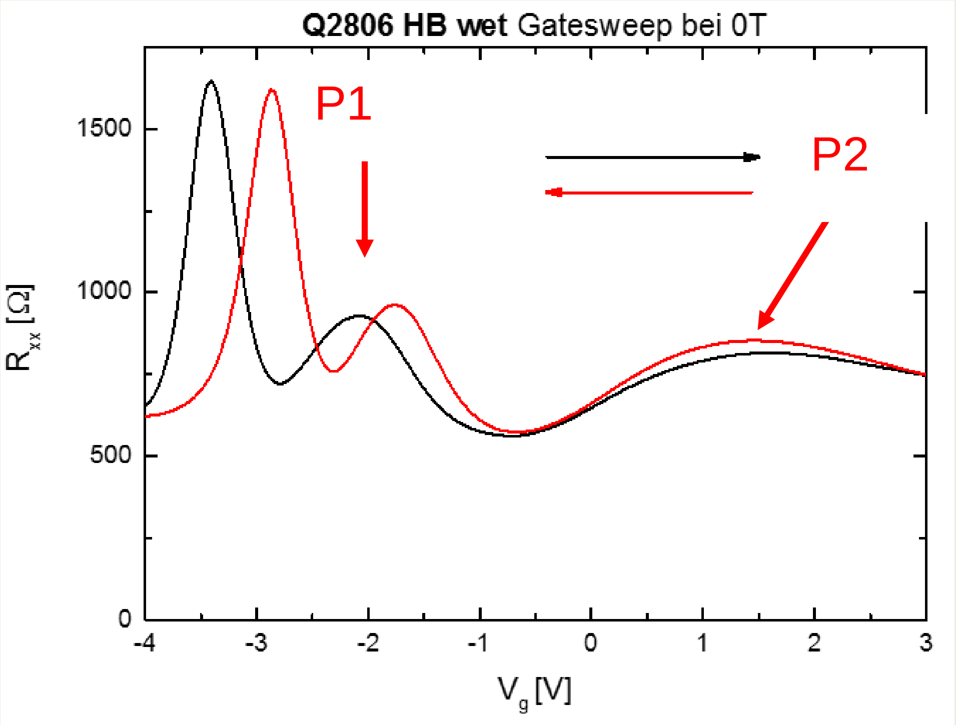
- Doped sample: Start from higher chemical potential
- Two additional resitance peaks
- The number of peaks and their energy separation depends on doping
- Exact path yet to be understood!

Broad electric field range : doped sample

RF capacitor (Paris)

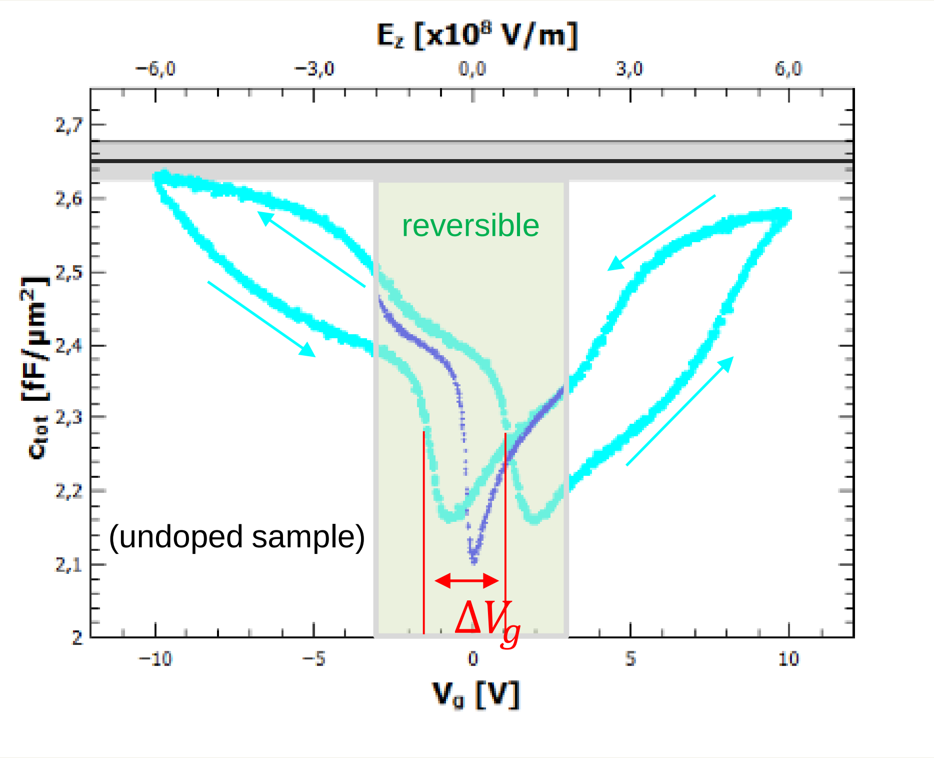


Hall-bar (Würzburg)



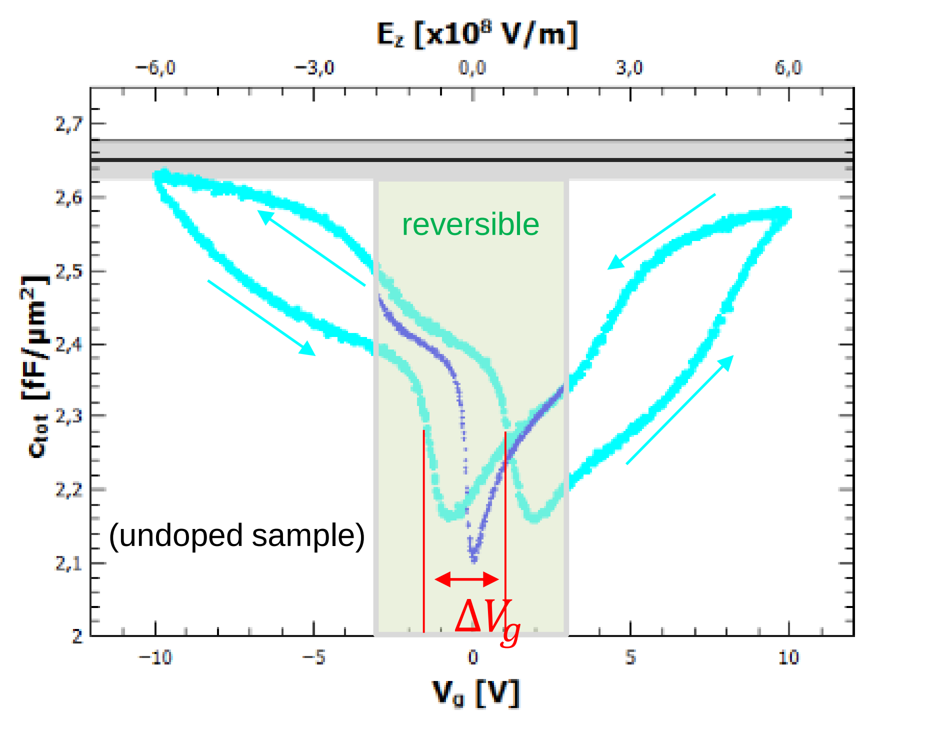
- Two additional resitance peaks
- No peak in the compressibility → scattering peaks
- Also seen in the Hall bar

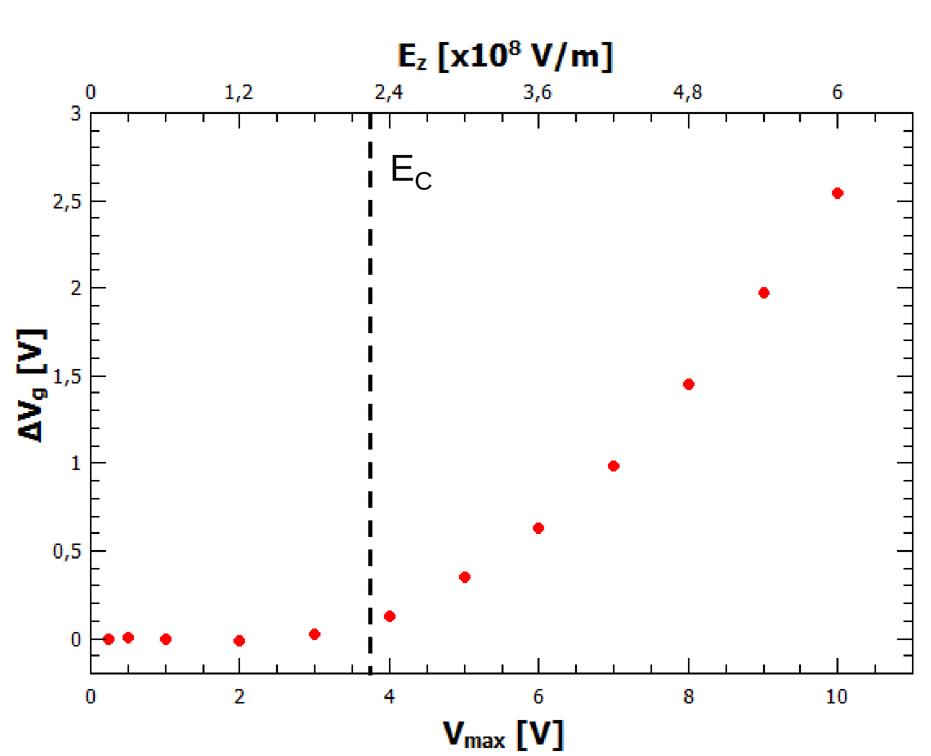
Further hints from hysteresis



- Meta-stability for large gate sweeps (observed on both samples)
- Upwards shift of capacitance minimum results in hysteretic cycles.

Further hints from hysteresis





- Meta-stability for large gate sweeps (observed on both samples)
- Upwards shift of capacitance minimum results in hysteretic cycles.
- Onset of meta-stability coincides with subband nucleation
- Meta-stability arises after TSS screening ``breakdown“.

Conclusions

Results presented in this talk:

- Quantitative measurement TSS compressibility $c_Q^{TSS}(\mu, |\vec{E}|)$
- Critical electric field for TSS screening identified, $E_c = 2.2 \cdot 10^8$ V/m
- Excited massive surface state model:
  - Critical electrical field E_c
  - Phenomenology below and beyond E_c

Thank you for your attention