POLITECHNIKA WARSZAWSKA

Resistivity and Surface resistance Measurements of SEMICONDUCTORS and Conductors

Jerzy Krupka

Warsaw University of Technology

Central Office of Measures, Poland

EMINDA project and EMMA-Club Meeting
Warsaw December 2012

Outline of presentation

- Introduction
- Basic definitions
- Measurements of bulk semiconductor samples
- Contactless measurements on wafers
- Resistivity measurements with split post and single post dielectric resonators
- Measurements of thin conducting and semiconducting films

Basic definitions

The complex permittivity of an isotropic material in general can be written as:

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon_r^{'} - j\varepsilon_{rd}^{''} - j\frac{\sigma}{\omega\varepsilon_0}) =$$

$$= \varepsilon_0 \varepsilon_r^{'} (1 - j \tan\delta_{eff})$$

$$\varepsilon_{eff}^{''} = \varepsilon_0 (\varepsilon_{rd}^{''} + \frac{\sigma}{\omega\varepsilon_0})$$

$$\tan\delta_{eff} = \tan\delta_d + \frac{\sigma}{\omega\varepsilon_0\varepsilon_r^{'}}$$

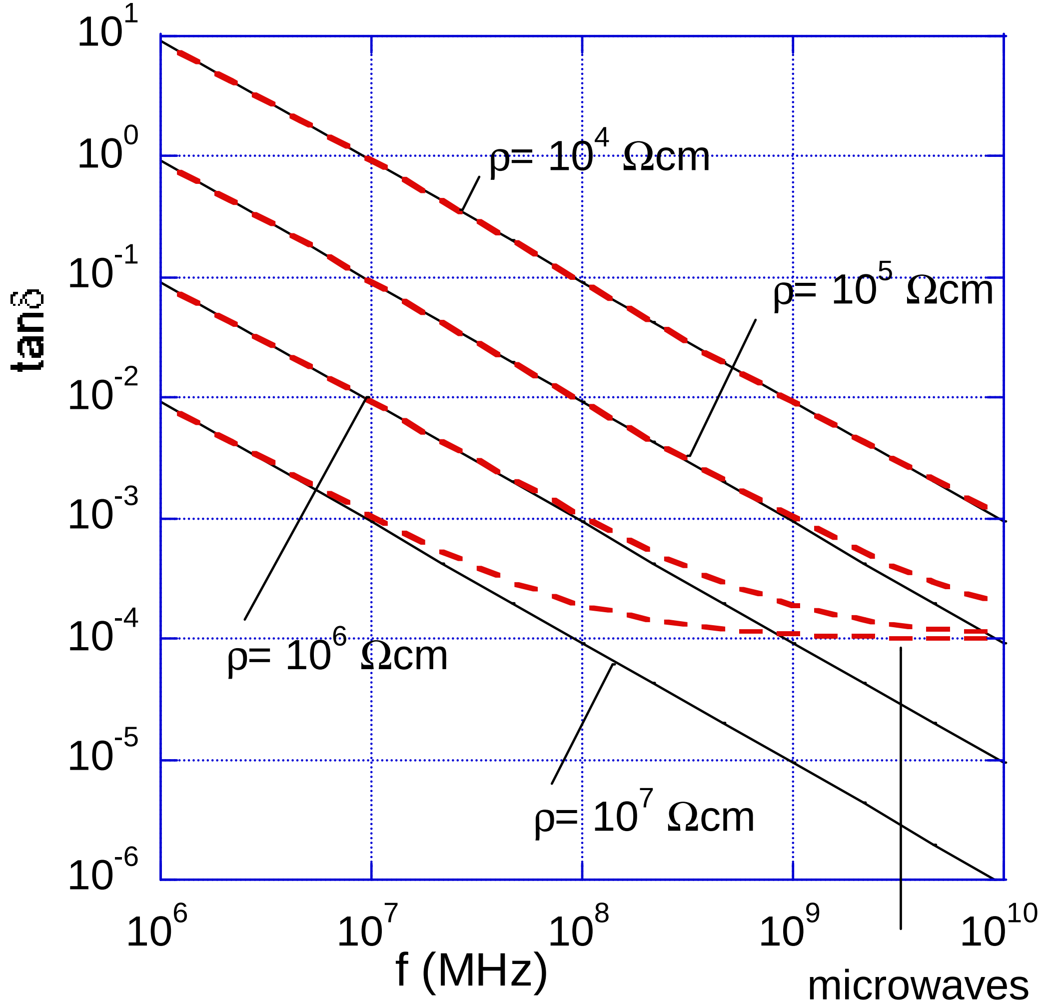
ε_0 - permittivity of vacuum
ω - angular frequency
σ - conductivity

$\tan\delta_d$ - dielectric loss tangent associated with pure dielectric loss mechanisms

Dielectric loss tangent versus frequency for HR semiconductors. Solid line – conductivity term, dotted line (red) – total

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

Conductivity (S/m)	Skin depth (microns) (5 GHz)
1.00E+03	224.49
1.00E+04	70.99
1.00E+05	22.44
1.00E+06	7.10
1.00E+07	2.24
5.00E+07	0.71

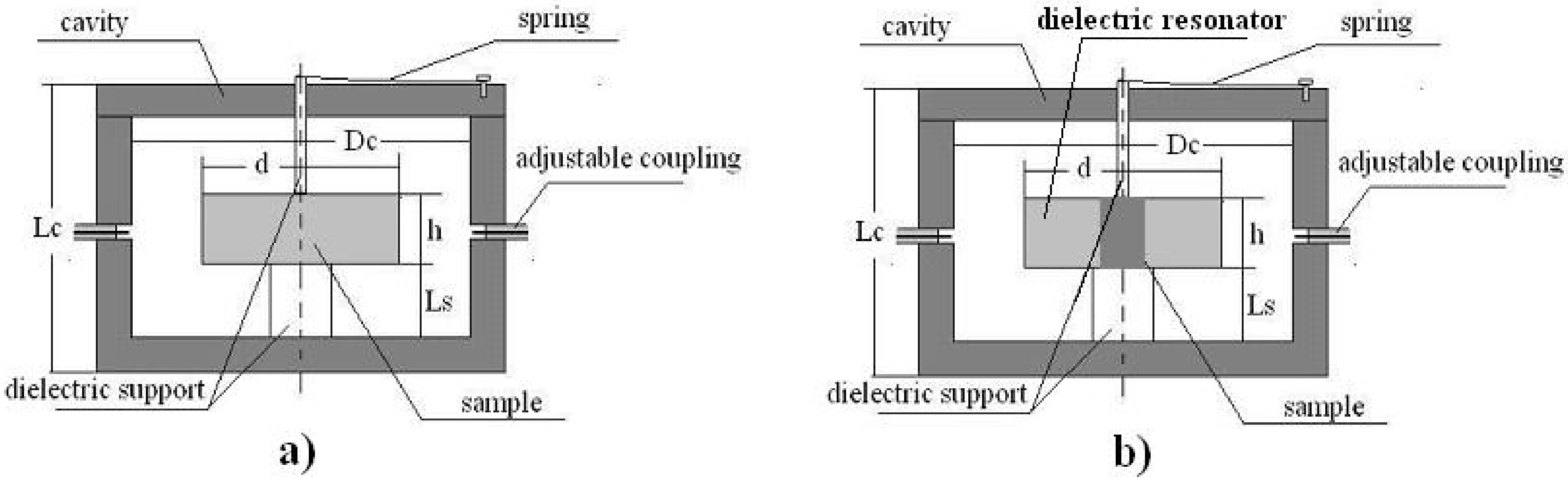


Measurements of bulk HR semiconductor samples employing dielectric resonator method

EMINDA project and EMMA-Club Meeting
Warsaw December 2012

Measurement techniques of bulk high resistivity

HR samples



Sketches of measurement fixtures used in experiments

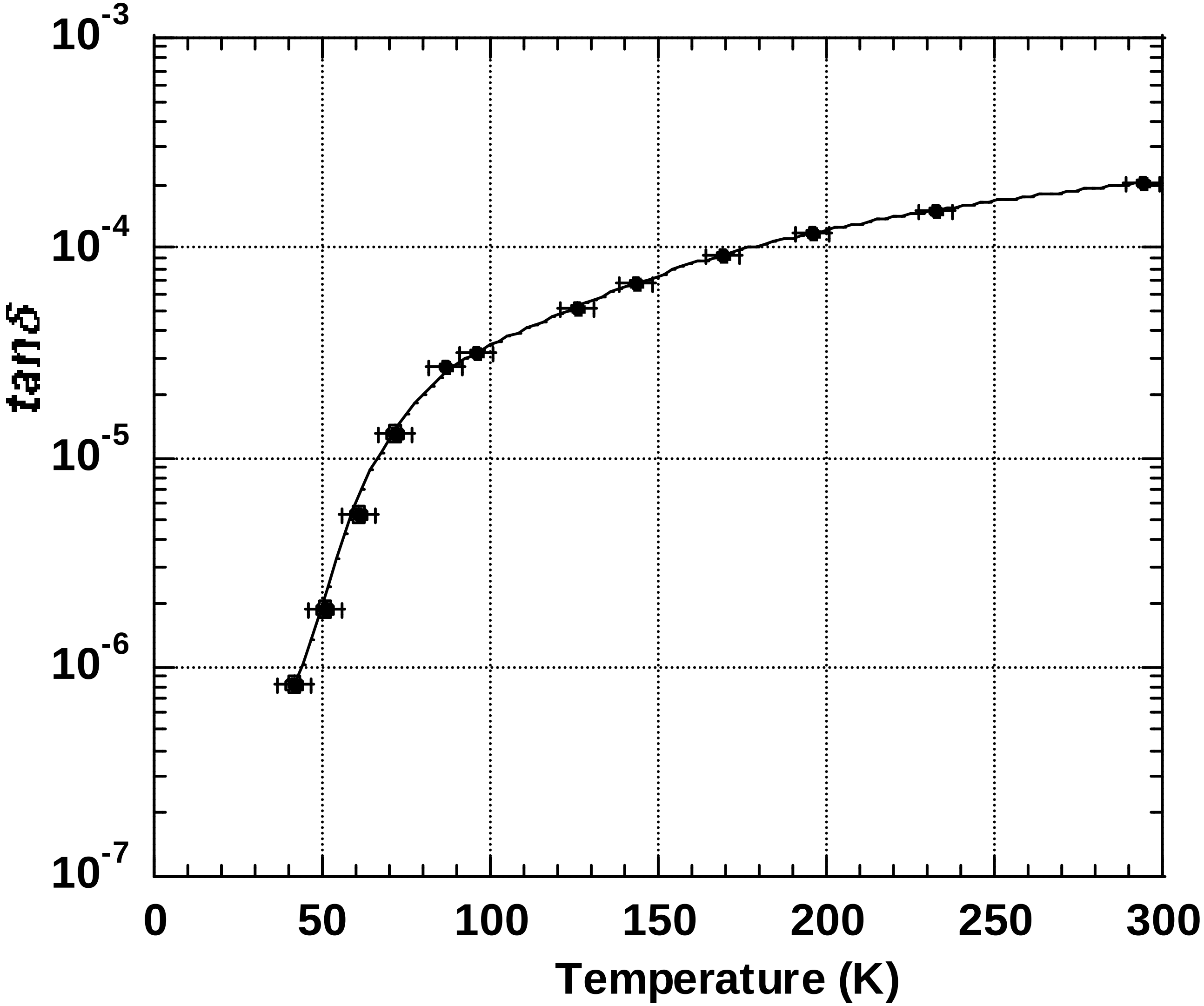
a) Useful only if tanδ <0.01

b) tanδ >0.1

Cryogenic measurement setup - photograph

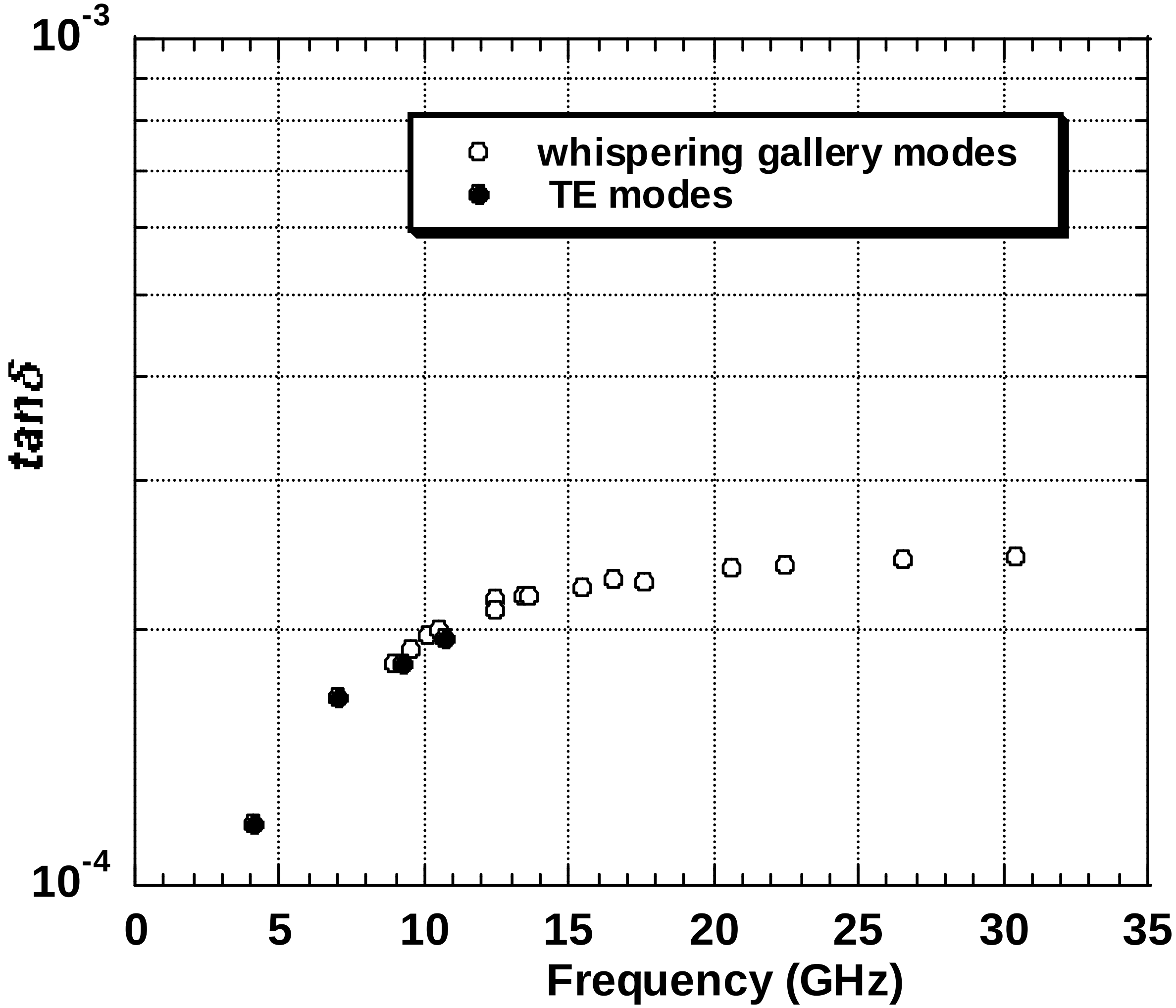
EMINDA project and EMMA-Club Meeting
Warsaw December 2012

GaAs



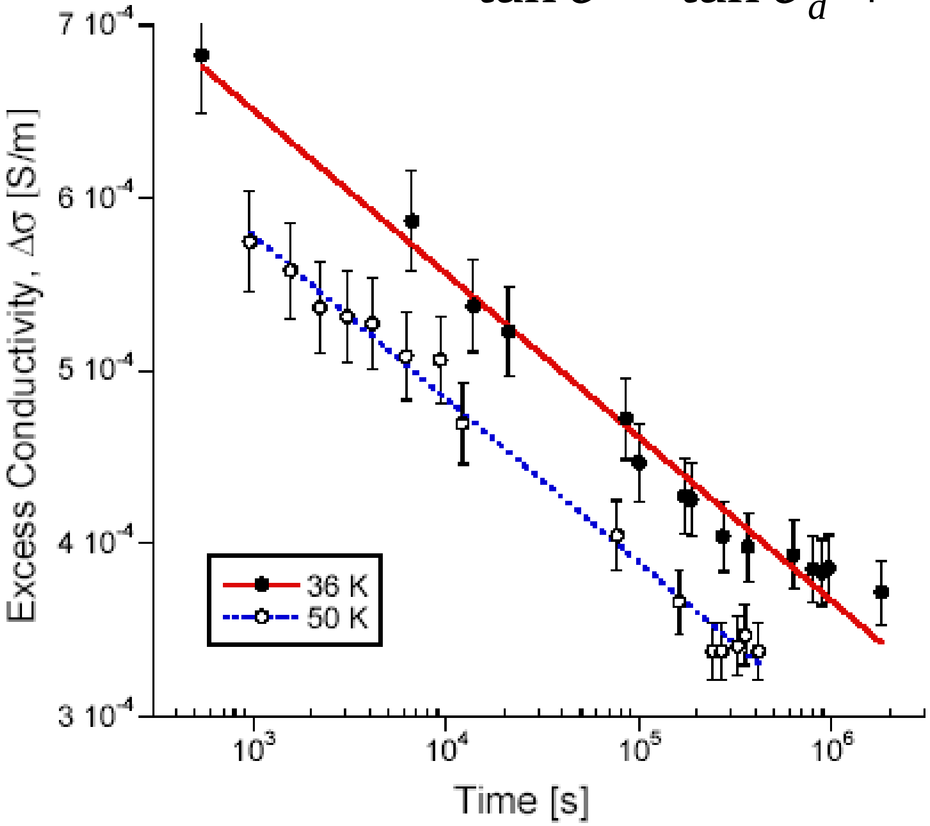
EMINDA project and EMMA-Club Meeting
Warsaw December 2012

GaAs (at room temperature)

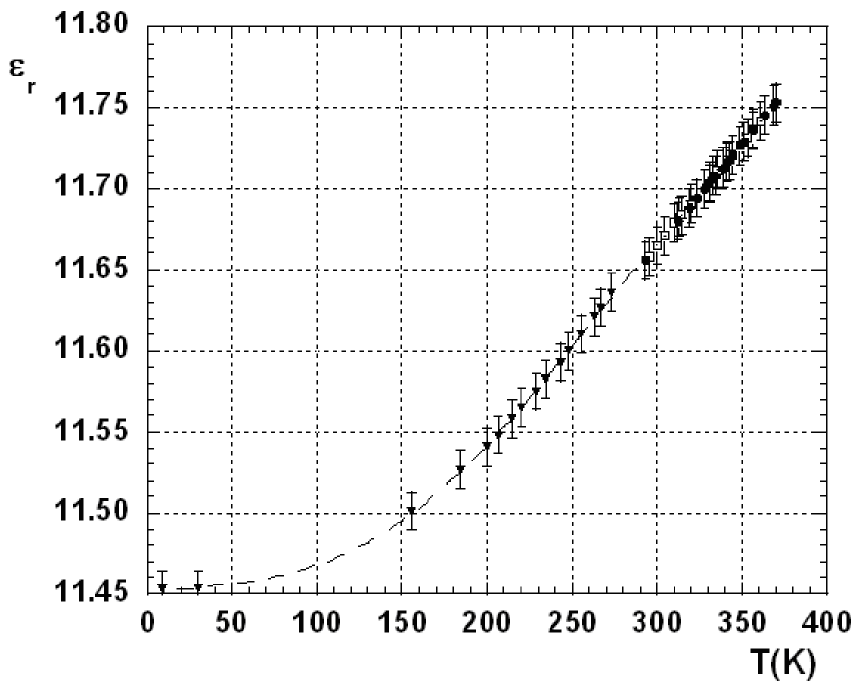


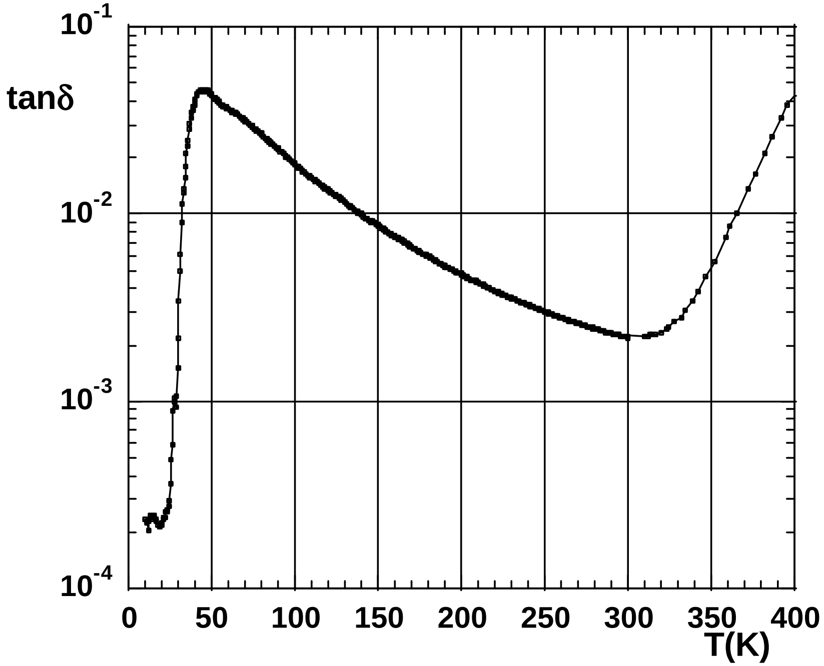
Persistent photoconductivity in bulk GaAs sample at cryogenic temperatures

$$\tan\delta = \tan\delta_d + \frac{\sigma_0 + \Delta\sigma}{\omega\varepsilon_0\varepsilon_r} = \frac{\sigma_{0eff}}{\omega\varepsilon_0\varepsilon_r} + \frac{\Delta\sigma}{\omega\varepsilon_0\varepsilon_r}$$

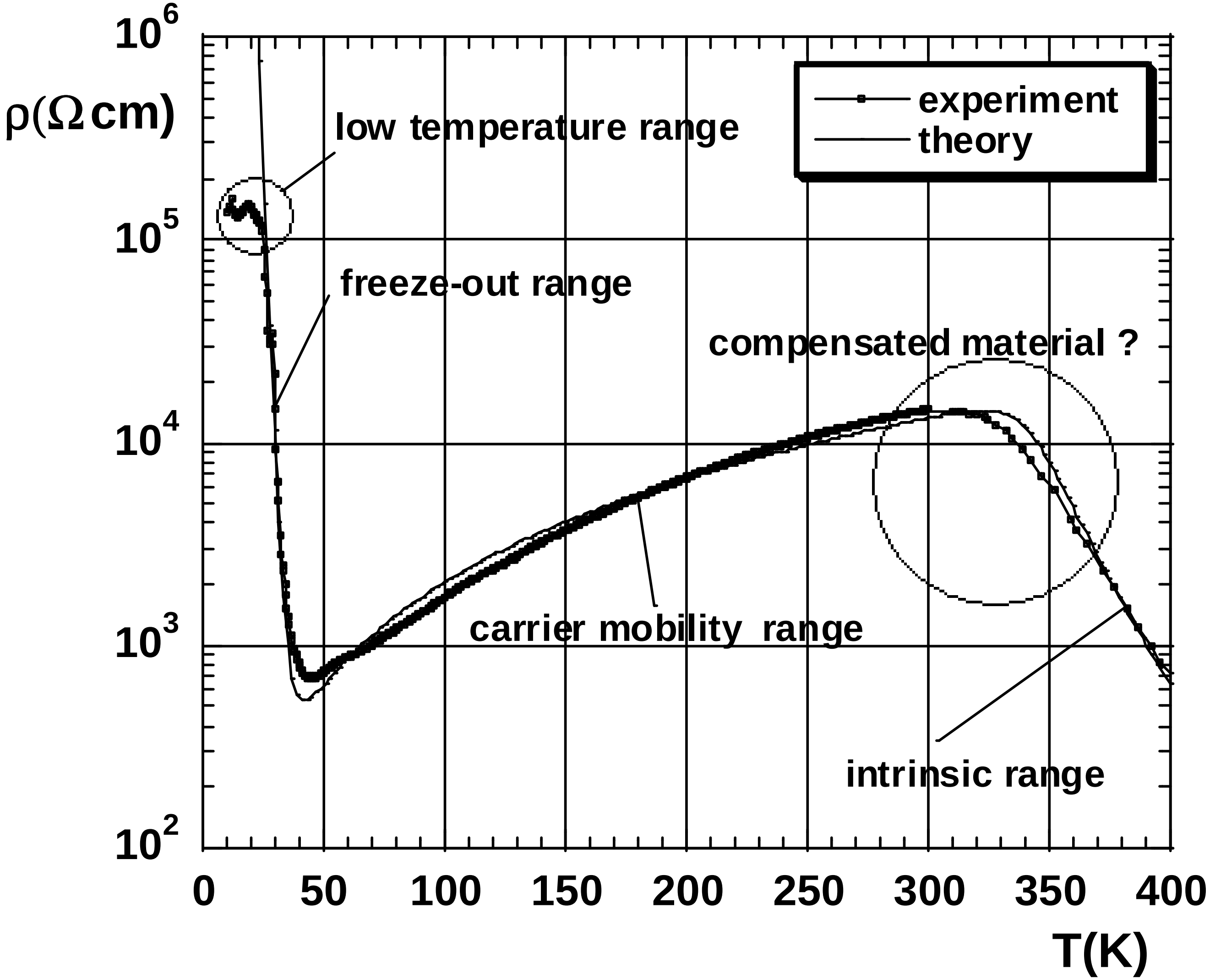


Permittivity and the dielectric loss tangent versus temperature for HR silicon at frequency about 4.98 GHz





Resistivity of HR Si versus temperature extracted from measurements at frequency about 4.98 GHz.



EMINDA project and EMMA-Club Meeting
Warsaw December 2012

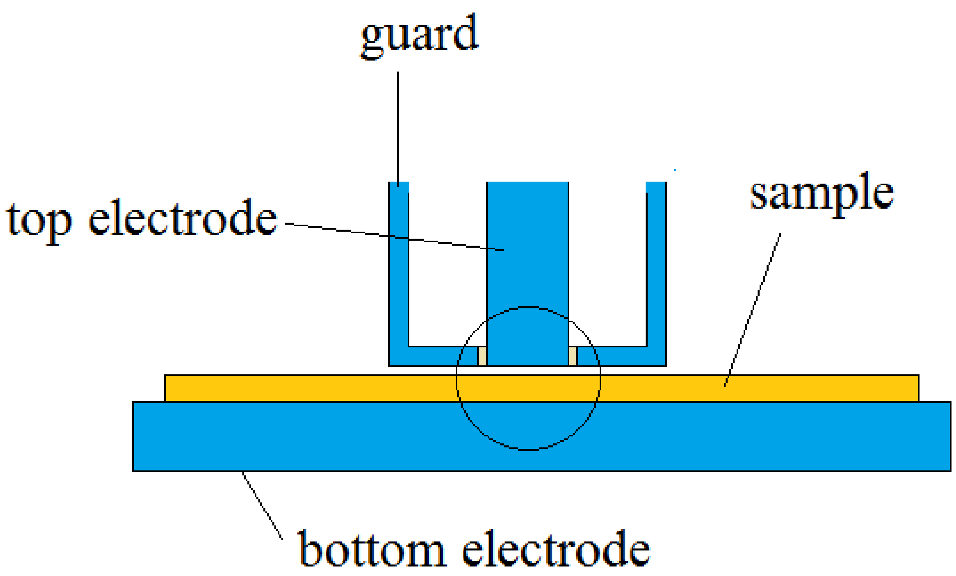
Contactless methods for resistivity measurements of semiconductor wafers and thin conducting films

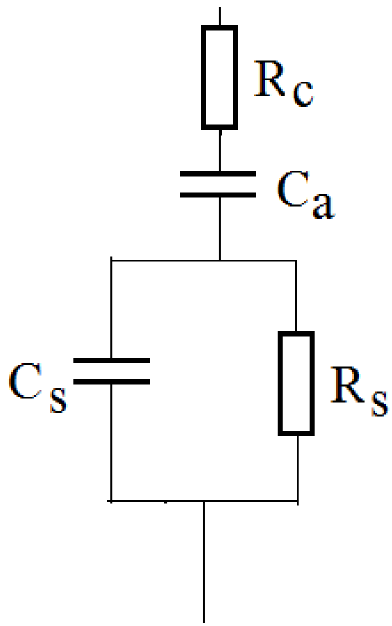
- Time domain and frequency domain capacitive techniques
- RF method (eddy currents)
- Split post dielectric resonators
- Single post dielectric resonators

Capacitive techniques

1) Time domain

Stibal R, Windscheif J and Jantz W 1991 *Semicond. Sci. Technol.* ***6 995-12001.***

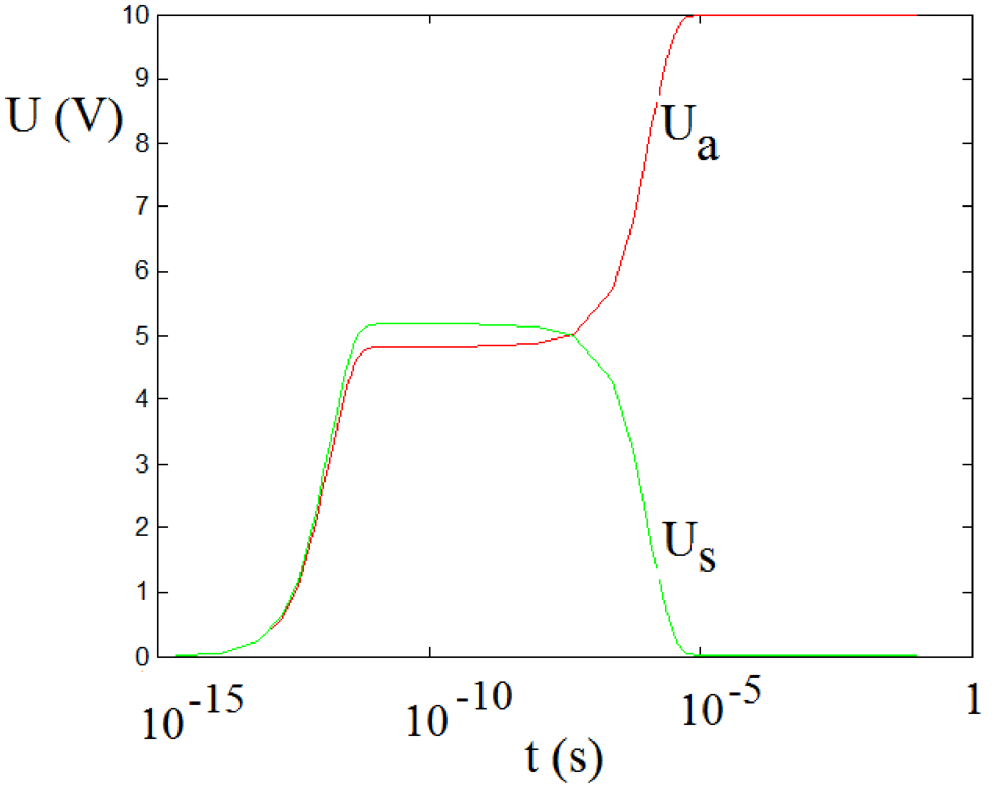




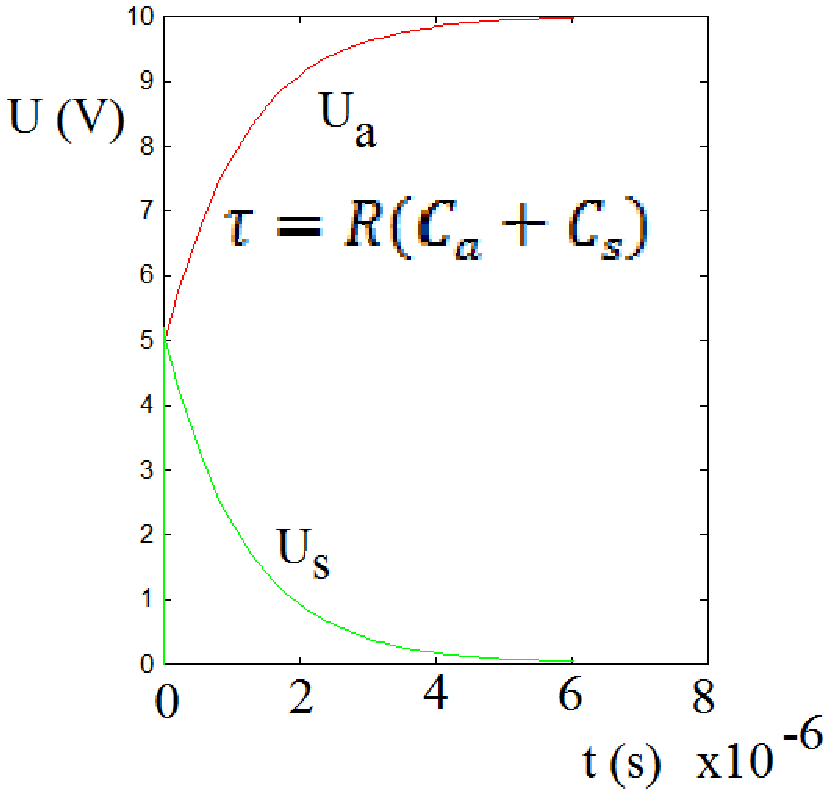
Time response for GaP sample having resistivity of $5.5\times10^5\ \Omega$cm

If Ca >> Cs the time constant does not depend on the size capacitor but only on permittivity and resistivity of material under test $\tau = \varepsilon_0 \varepsilon_r \rho$

Otherwise $\tau = R(C_a + C_s)$



log scale



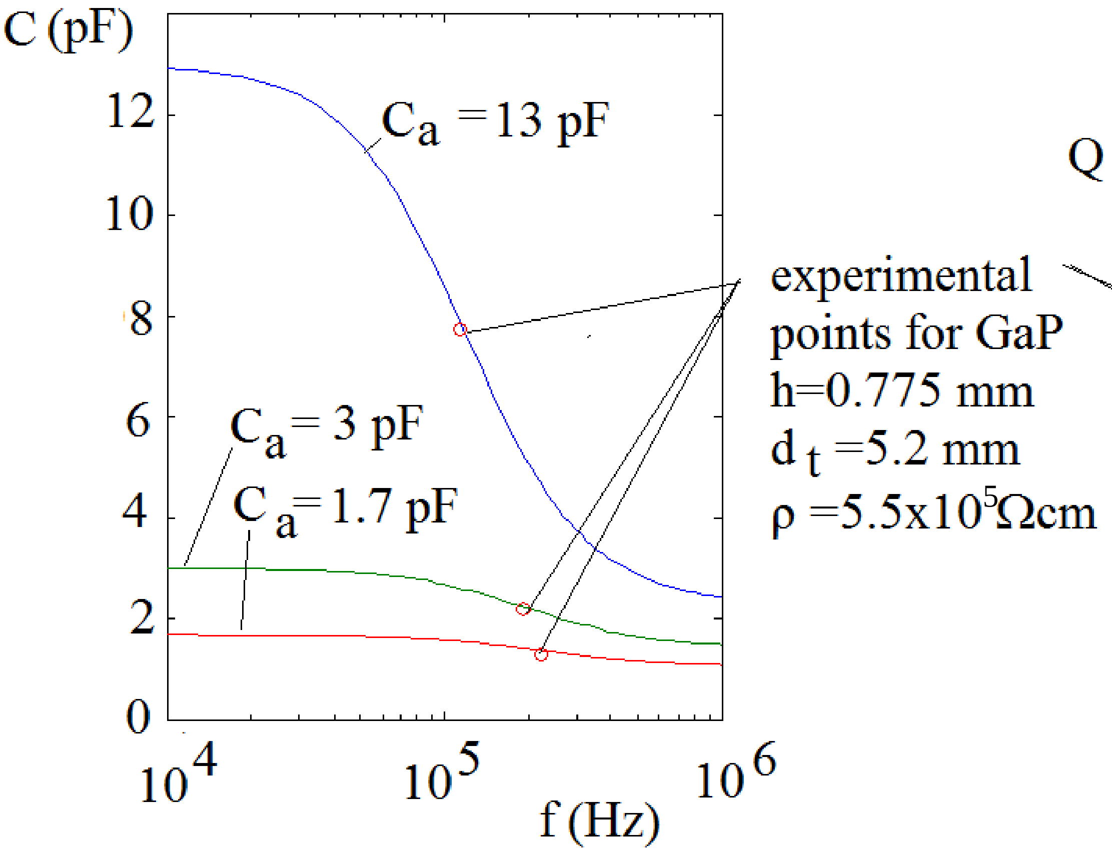
linear scale

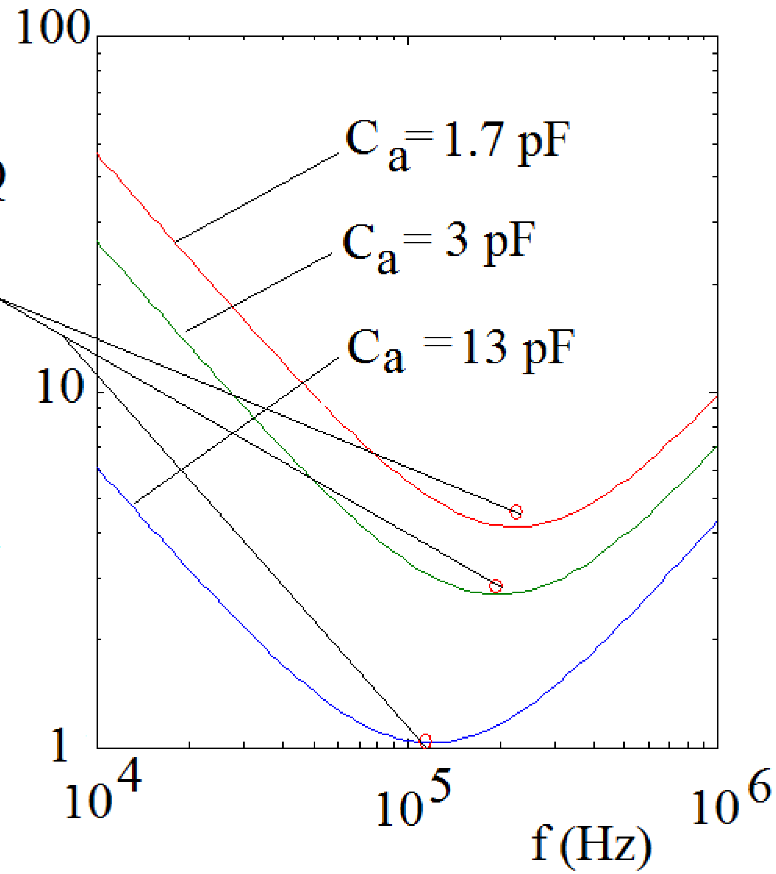
2) Frequency domain:

D. Siebert , Physik der Kondensierten Materie, **2**, 394, 1964

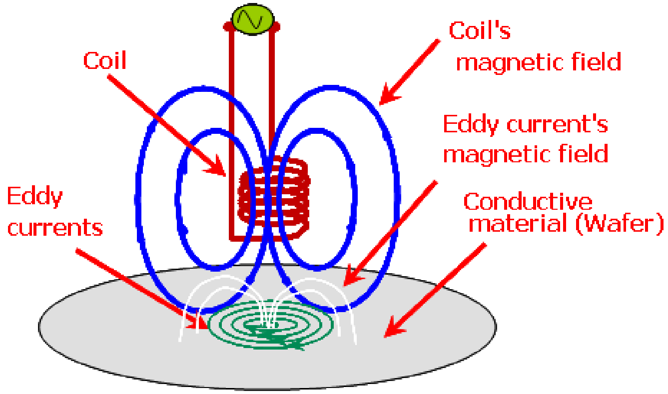
Frequency responses for GaP sample having resistivity of 5.5x10^5 Ωcm

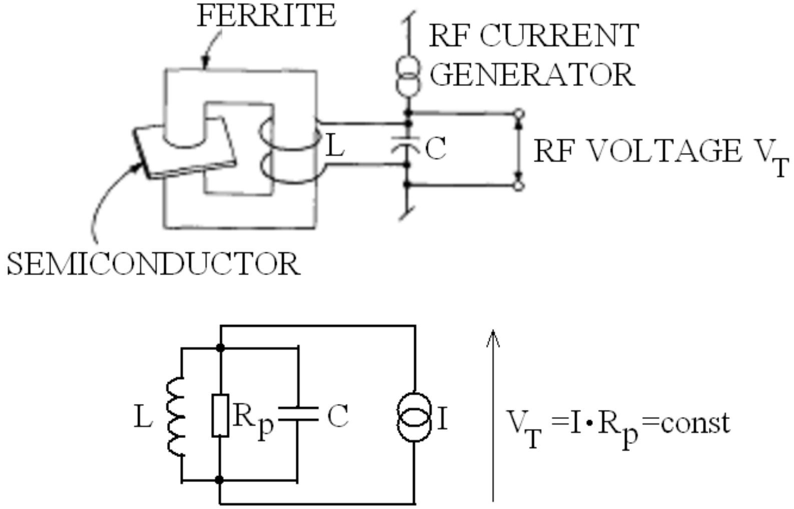
$$f_{min}^{-1} = 2\pi R_S \sqrt{C_S(C_S + C_a)}$$

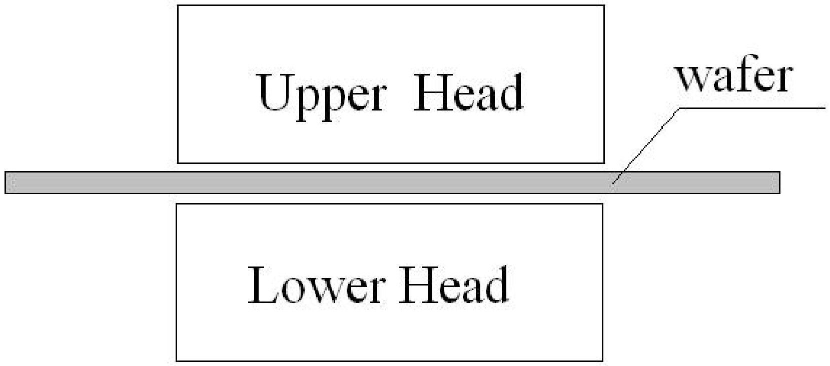




Contactless method for measurements of resistivity of semiconductors at RF (Lehighton Inc.)

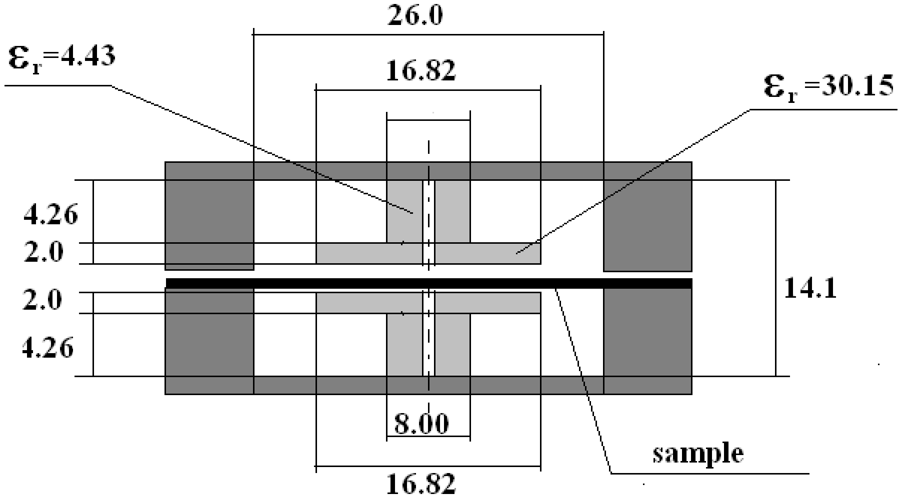


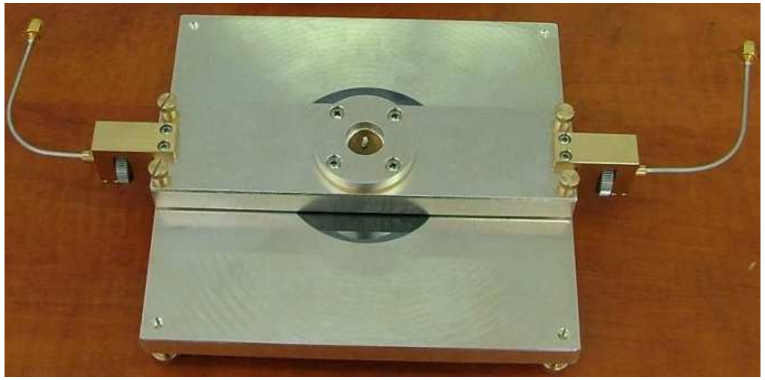




[1] G. L. Miller, D. A. H. Robinson, and J. D. Wiley, "Contactless measurement of semiconductor conductivity by radio-frequency-free-carrier power absorption" *Rev. Sci. Instrum*. Vol. 47, No. 7, pp. 799, 1976

Split post dielectric resonator 5 GHz





Results of measurements for thin films

f (MHz)	Q	h(mm)	Rs (Ω)
5127.4	12558	blank substrate	
5127 .0	100	0	3.2705E+03
5127.0	1000	0	3.5251E+04
5127 .0	12200	0	1.3652E+07

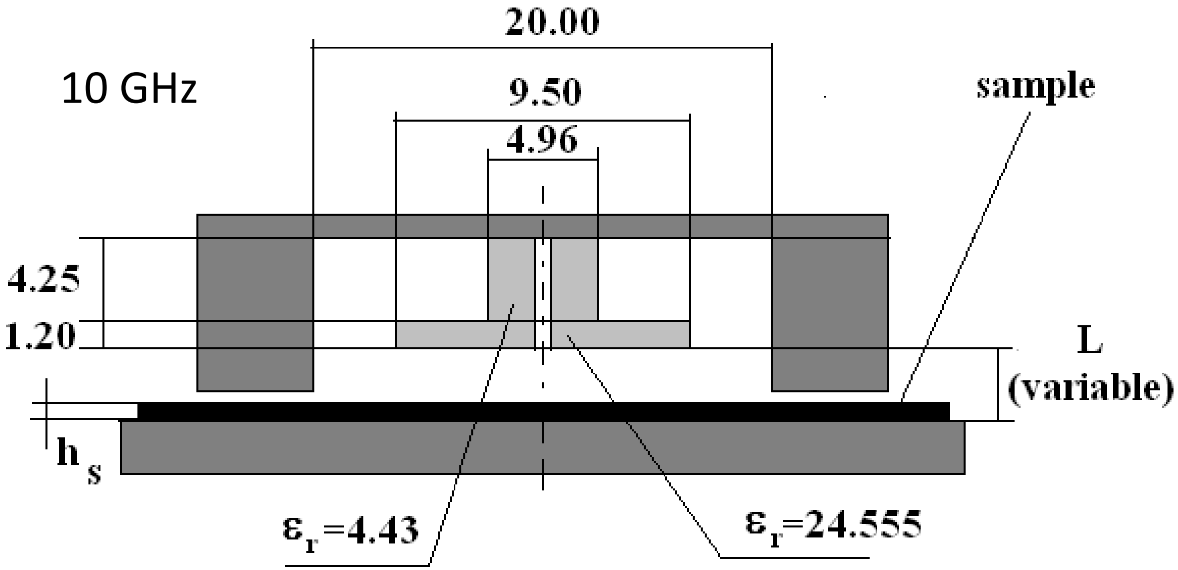
Results of measurements for wafers

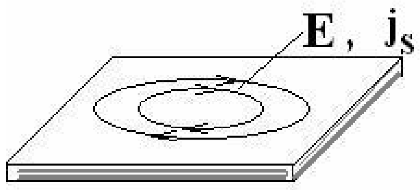
h(mm)	ε_r	tanδ	ρ (Ωcm)	
.438	9.402	3.9494E-06	9.62E+06	Sapphire
1.500	4.422	3.1873E-05	2.54E+06	Quartz
.995	11.645	2.5582E-03	1.23E+04	Silicon

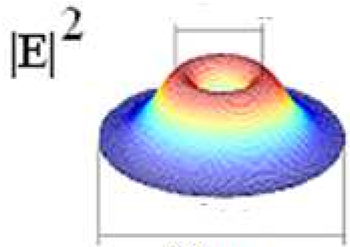
Single post dielectric resonators (SiPDR)

10 GHz

10 GHz





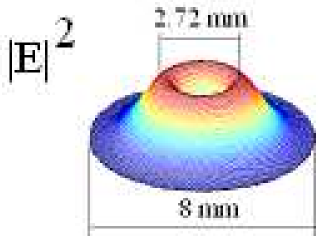


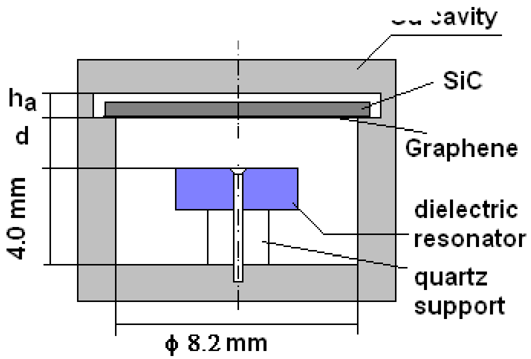
Measurement range

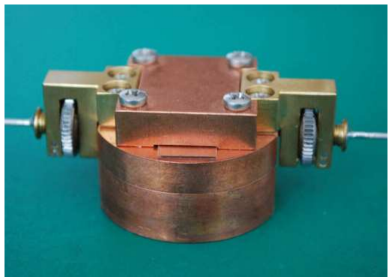
$10^{-1} < Rs < 10^{4}\ \Omega$

Inverted single post dielectric resonators

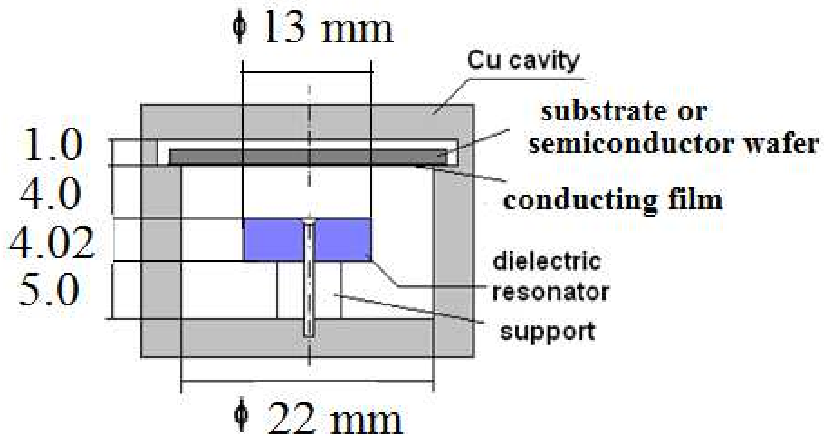
13.5 GHz

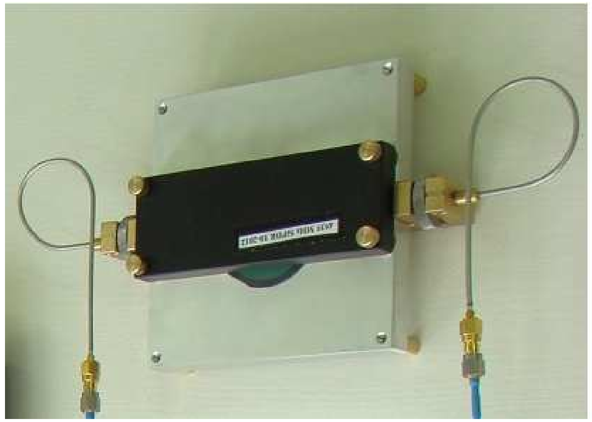






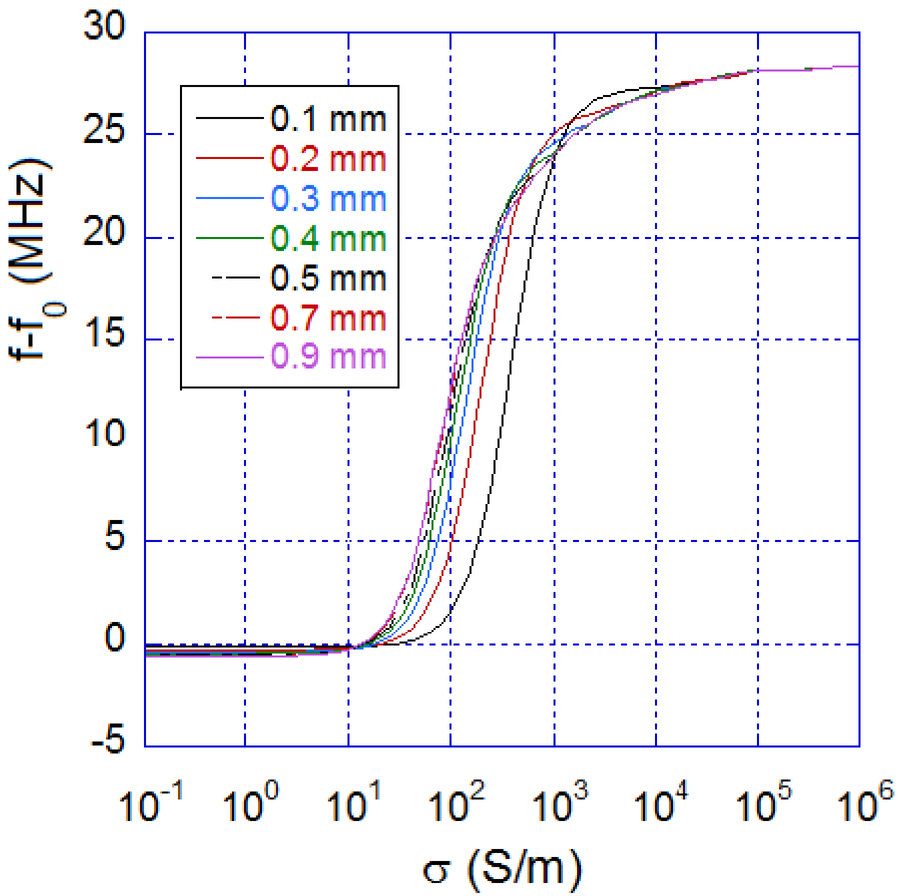
5 GHz

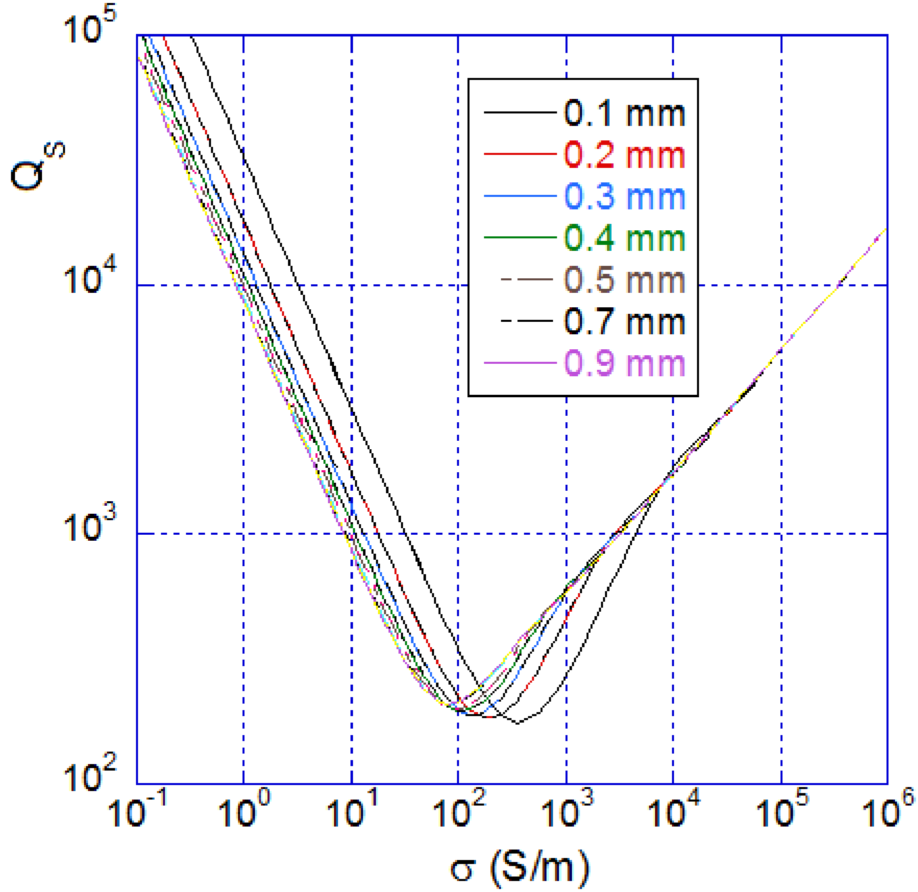




J. Krupka and W. Strupiński, “Measurements of the sheet resistance and conductivity of thin epitaxial graphene and SiC films”, Applied Physics Letters, Vol.96, 08210, 2010

Resonance frequency shifts and Q-factors due to losses in semiconductor wafers for 5 GHz SiPDR

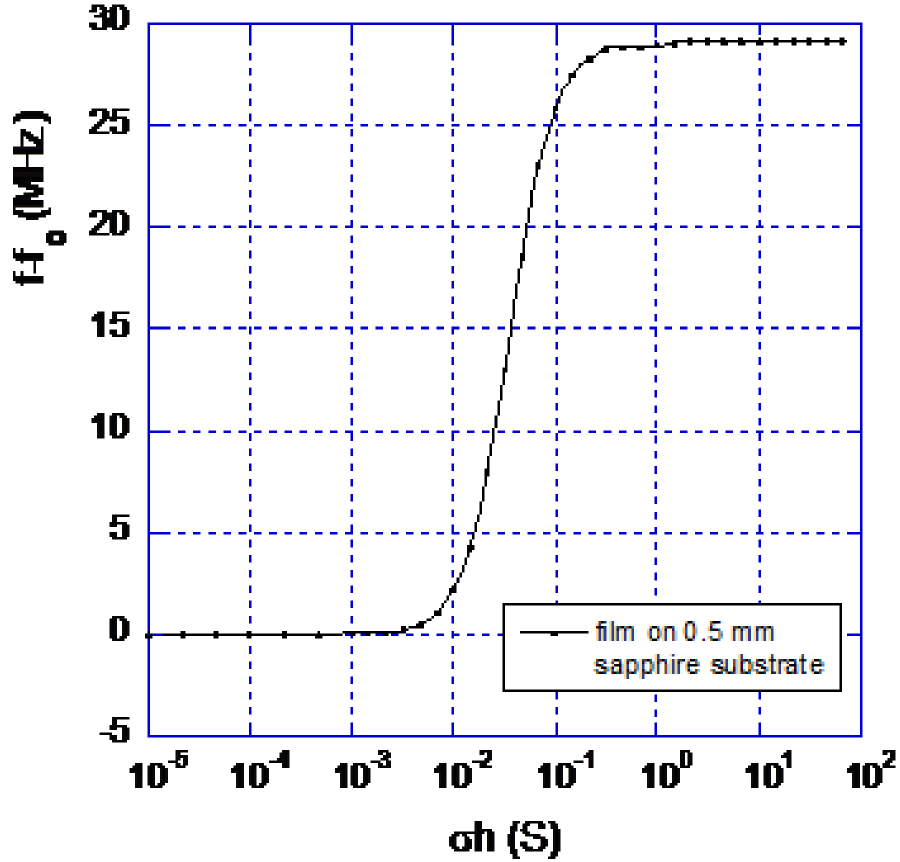


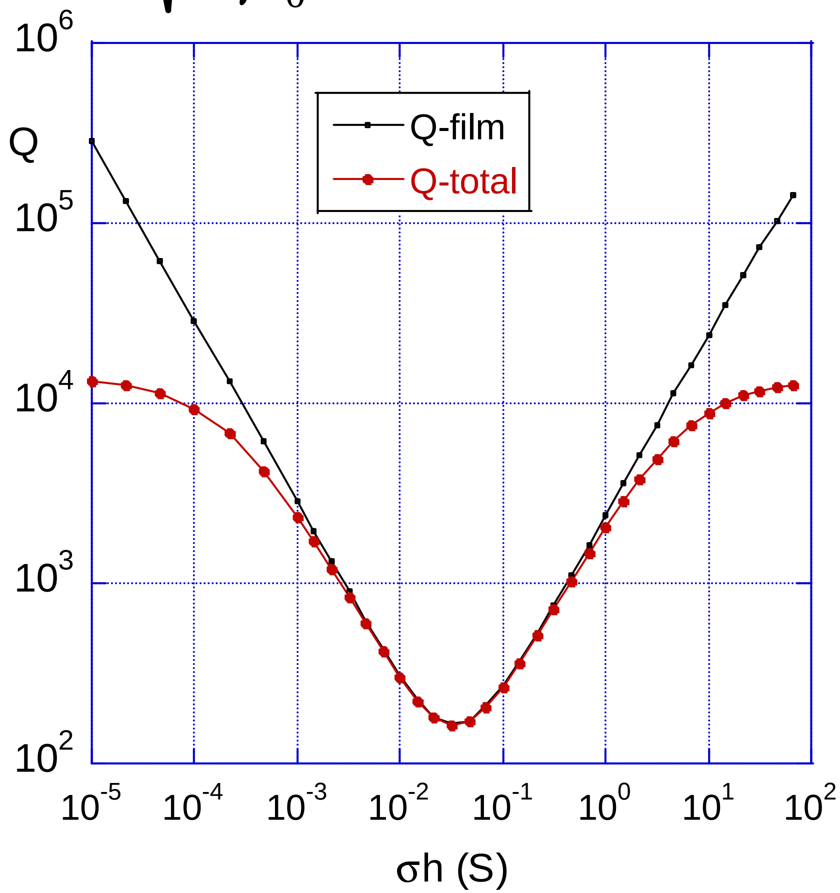


Resonance frequency shifts and Q-factors due to losses in thin conducting films for 5 GHz SiPDR

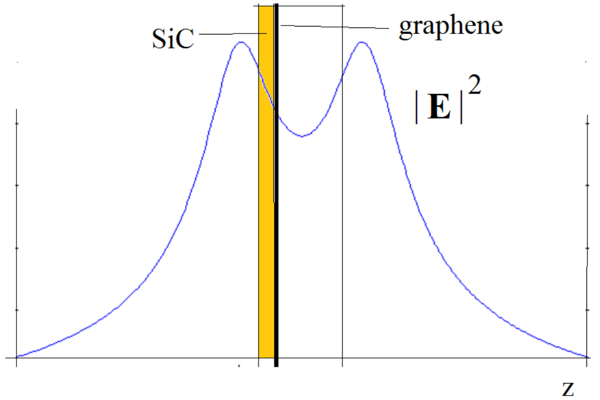
thin conducting film: $h_S < \delta$

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \sigma}}$$

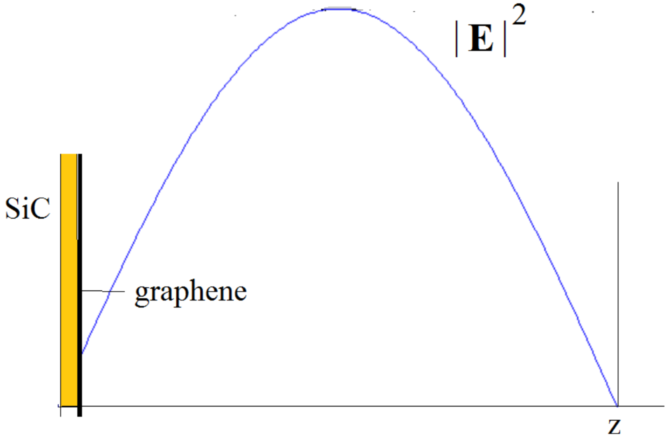




Differences in sensitivity of measurements between SPDR and SiPDR

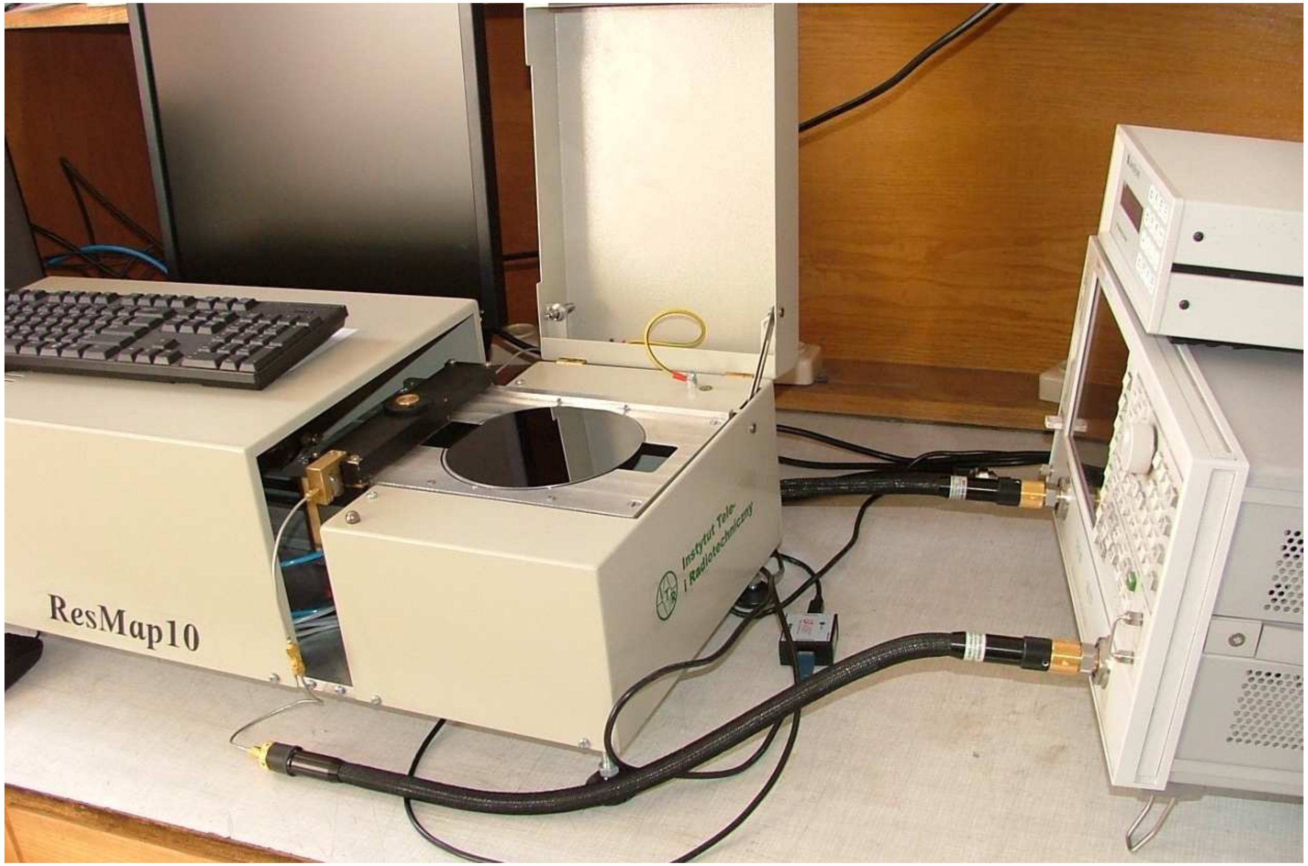


Axial distribution of electric field energy in SPDR

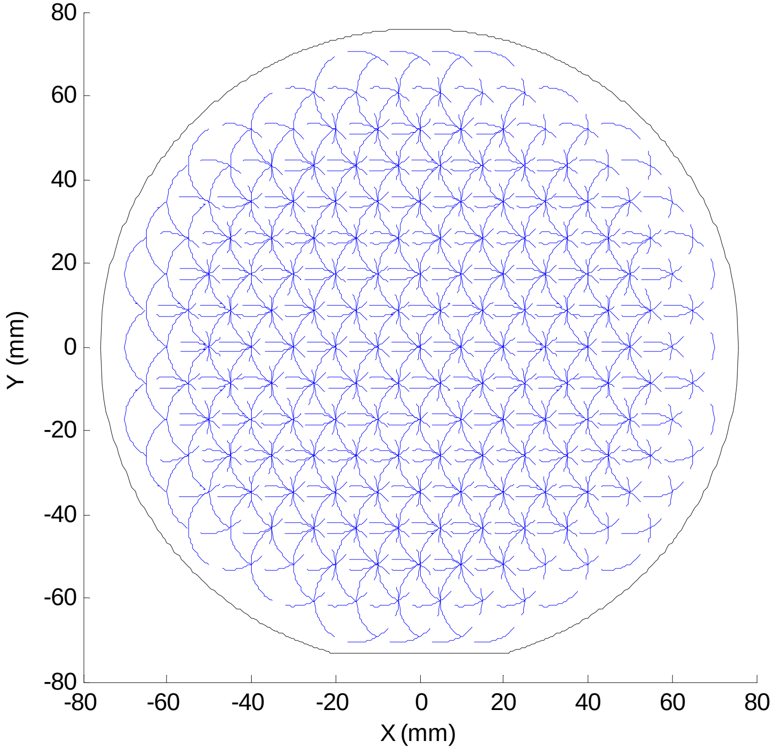


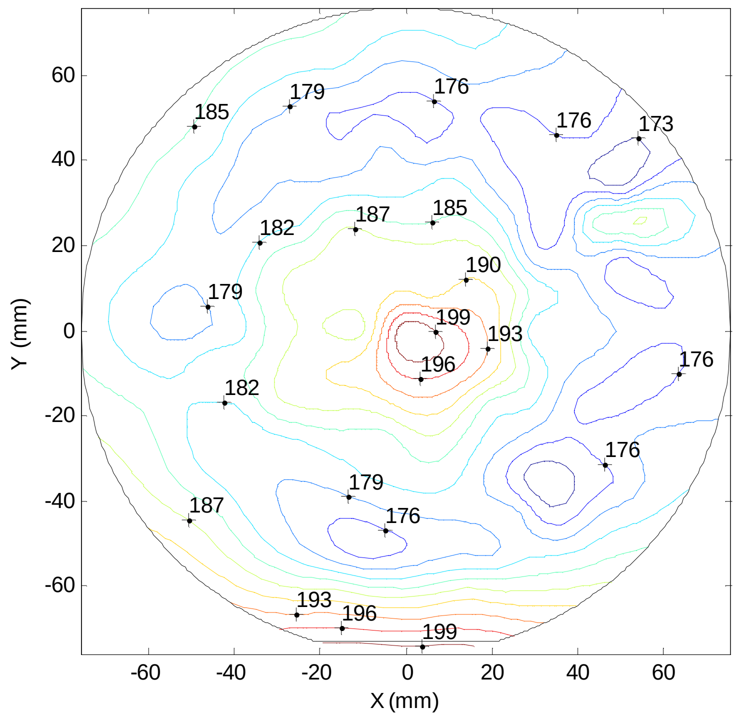
Axial distribution of electric field energy in SiPDR

Resistivity mapping of HR semiconductors and high sheet resistance films employing SPDR (5 GHz)

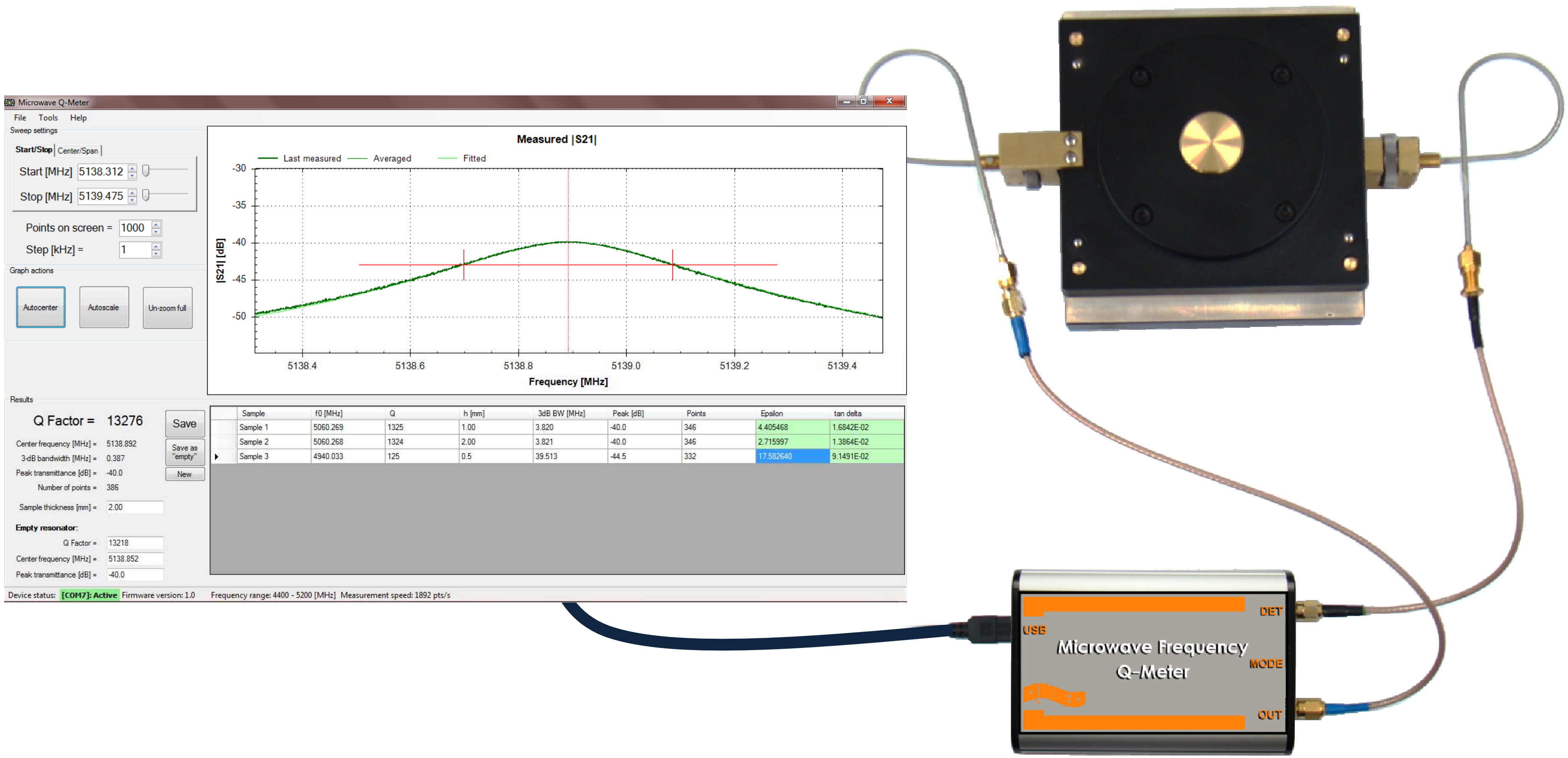


Resistivity map on HR Si sample 6” (TOPSIL). Resistivity scale in Ωm

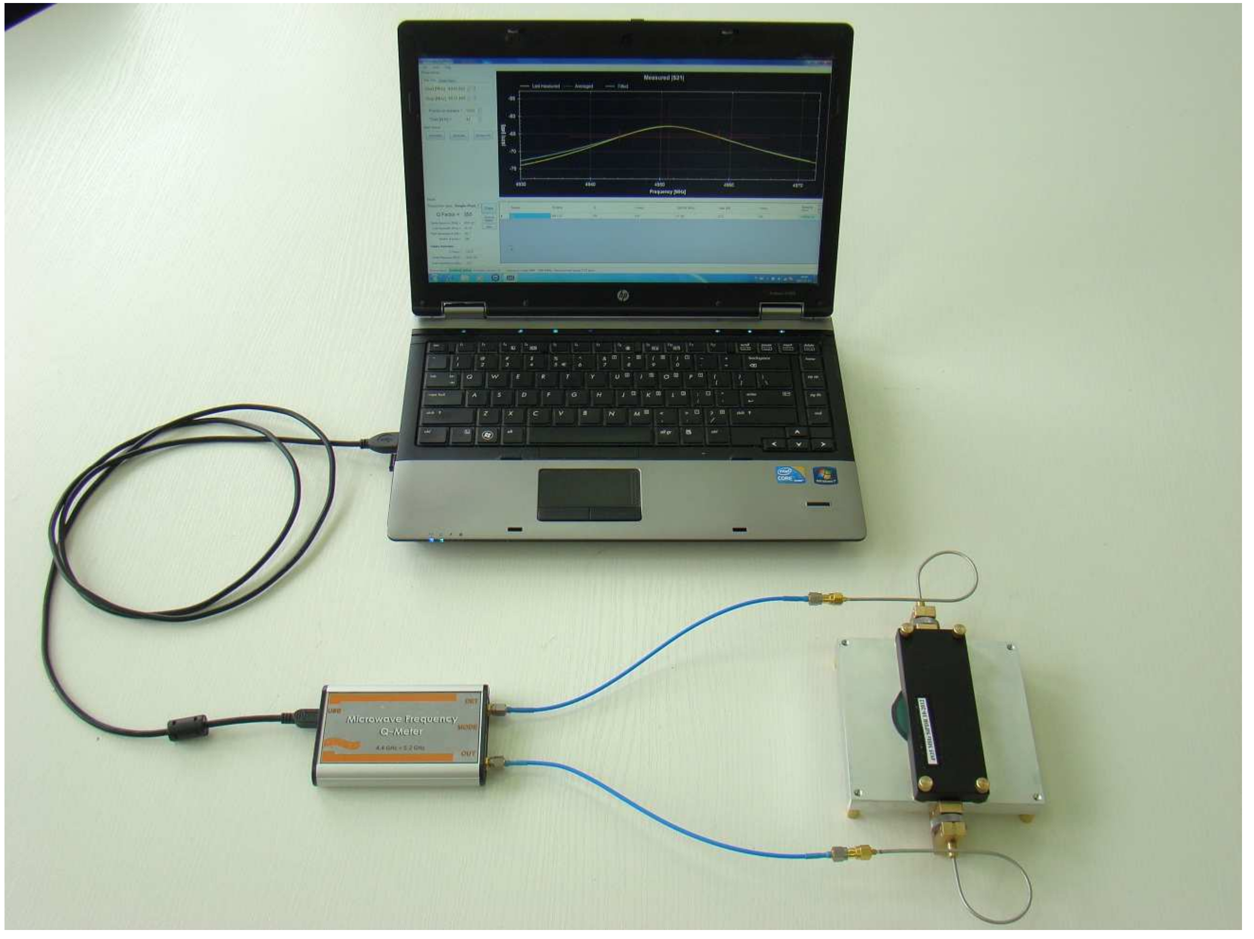




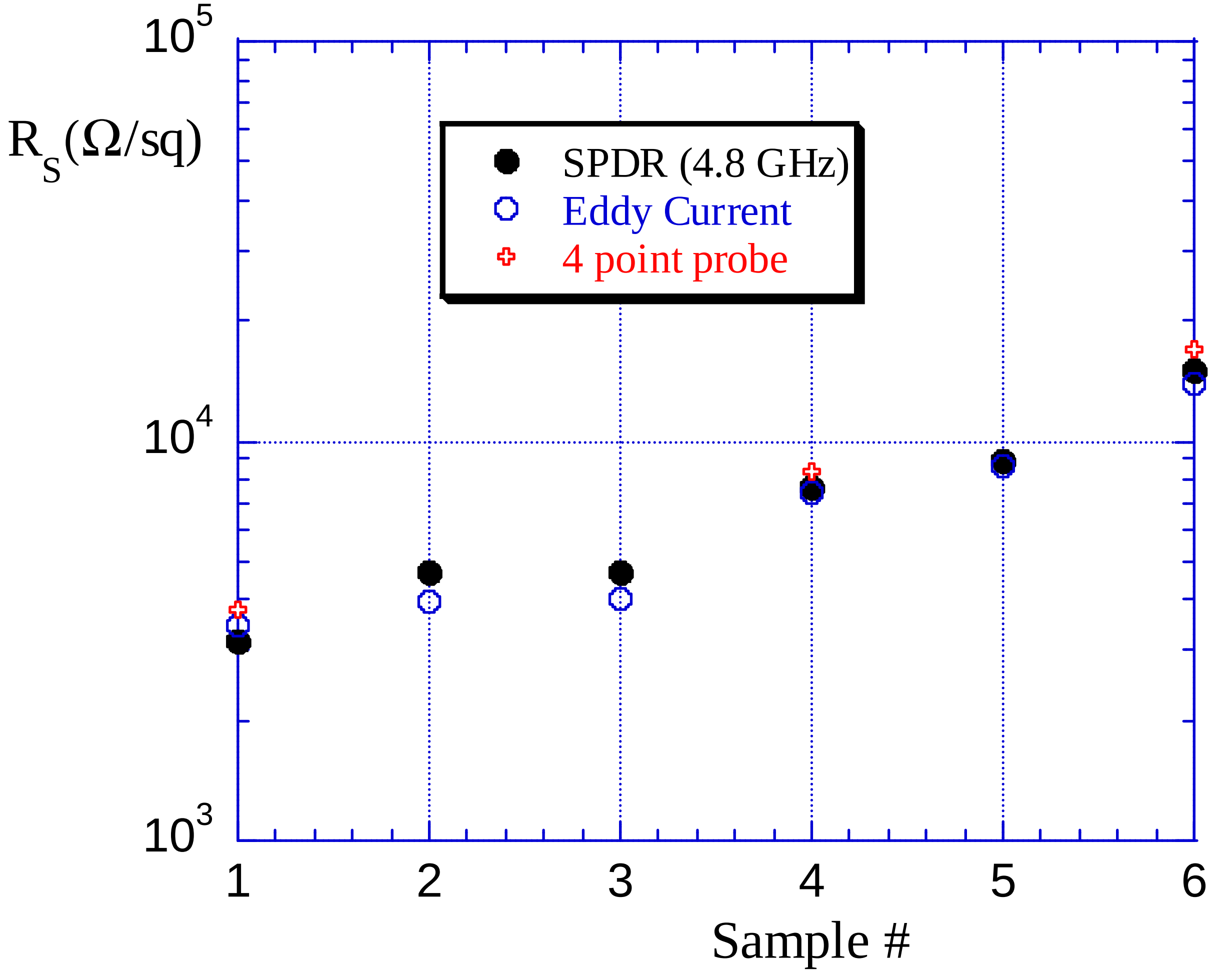
Cheaper alternative



Photograph of 5 GHz resistivity meter



Measurement results employing 3 different methods

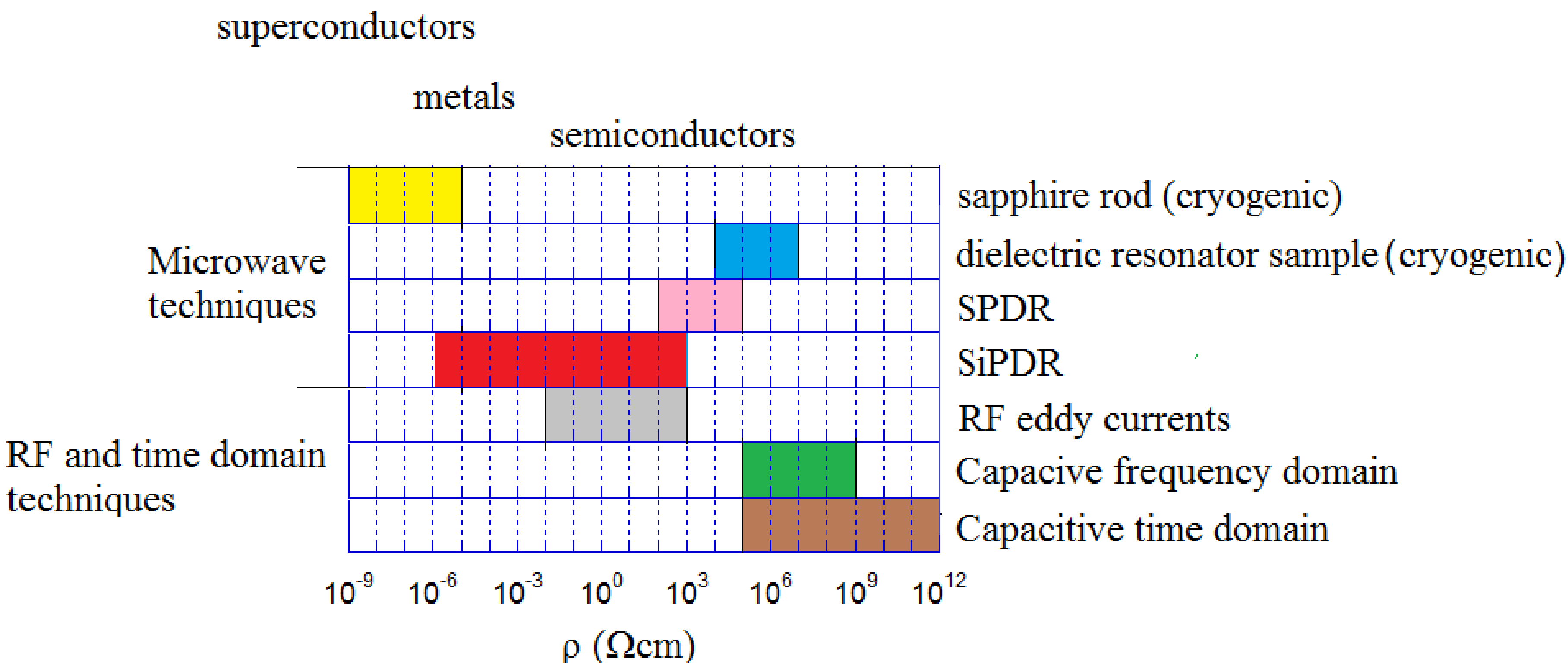


J.Krupka, Danh Nguyen, and J. Mazierska, "Microwave and RF Methods of Contact less Mapping of the Sheet Resistance and the Complex Permittivity of Conductive Materials and Semiconductors", **Measurements Science and Technology**, vol.22, 085703 (6pp), 2011

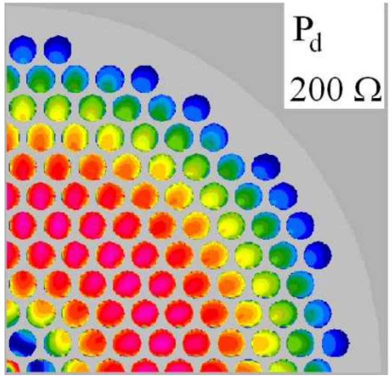
Eddy current, SPDR and SiPDR methods

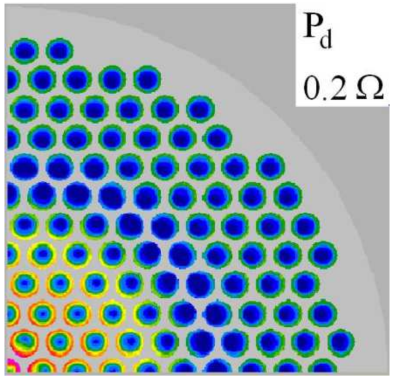
Parameter	Eddy current method	SPDR	SiPDR
Min. area/ thickness	14mm/0.9mm	20mm/1mm 10mm/0.5mm	20mm/1.2mm 8mm/0.5mm
Measurement range Rs (Ω)	0.1 Ω–10 kΩ	4 kΩ – 10 MΩ	0.1 Ω – 10 kΩ
Measurement range ρ(Ωcm)	$5x10^{-3}$ -10^{3} Ωcm	$200\text{-}10^{5}$ Ωcm	10^{-5}- 10^{3} Ωcm
Calibration standards	Necessary	Not necessary	Not necessary
Additional equipment	Not necessary	Necessary (ANA or Q-meter)	Necessary (ANA or Q-meter)
Substrates (for films)	Semi-insulating	Semi-insulating	Semi-insulating or arbitrary for $h>3\delta$

Summary of contactless methods

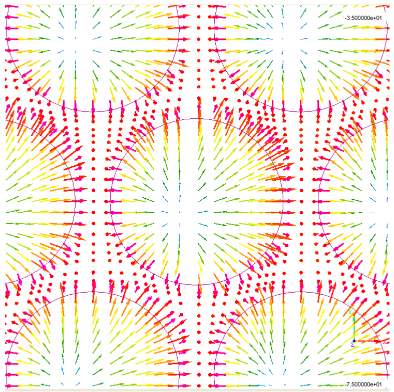


Electromagnetic field interaction with not continuous conducting layers placed in SPDR

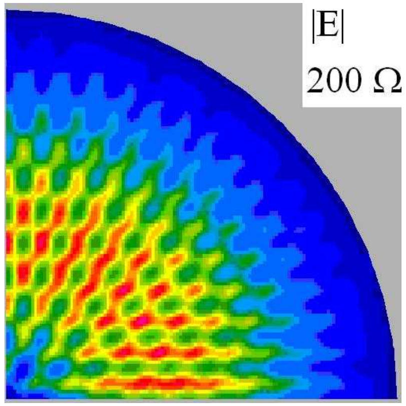


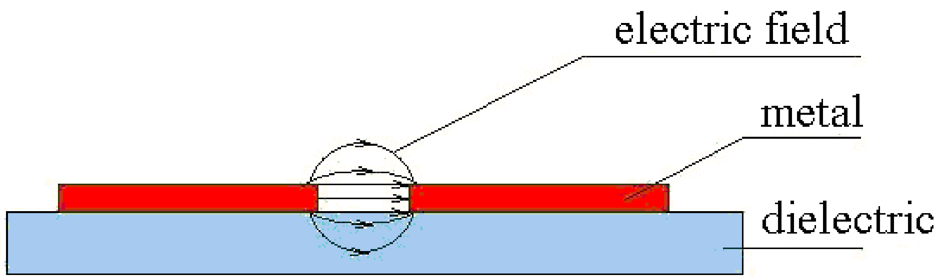


EM power dissipated



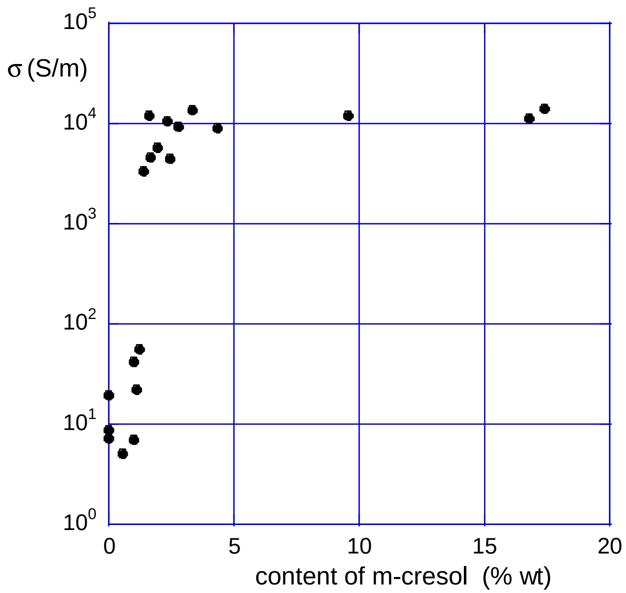
Magnetic field distribution around metal islands 0.2Ω





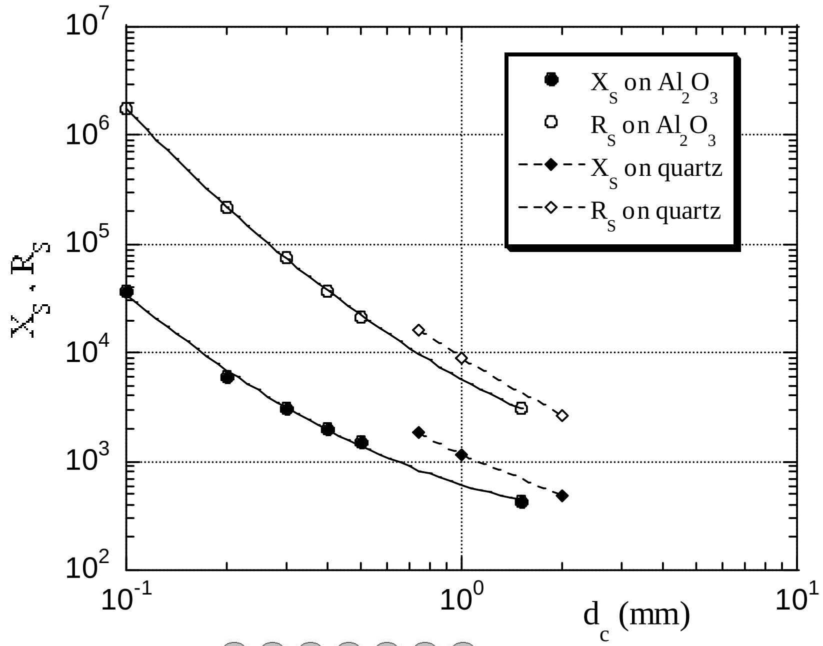
Electric field distribution

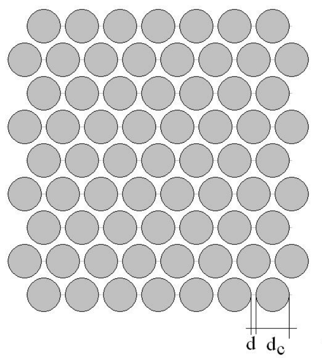
Conductivity and sheet impedance above and below percolation threshold



Effective conductivity of thin polyaniline films

M Popis, J. Krupka, I. Wielgus, and M. Zagórska, **Ferroelectrics,** Vol. 388, Pages: 5-9, 2009





$$X_S = \frac{1}{\omega \varepsilon_0 \varepsilon_r^{'} h_f}$$

Number of Institutions from particular countries that purchased resonators manufactured by QWED