Non Contact Electrical Characterization of PV Films

Jan Obrzut, NIST, MML, Div 642 (jan.obrzut@nist.gov)

Contributors: Xiaohong Gu, NIST, EL

- **Review of conductivity/dielectric/insulation resistance testing**
  - Direct Current (DC) Insulation Resistance Standard Test (IEC 62788-1-2, 2014 developed for PV insulators)
  - Alternating Current (AC) Insulation Resistance Test (ASTM D149 modified for printed circuit boards dielectrics)
  - Brief intro to polarization and conduction processes in dielectrics
  - real and imaginary AC conductivity
  - correlation between DC and AC conductivity
- Non-contact AC conductivity measurement using a 7 GHz resonant cavity
  - AC conductivity of PET – effect of exposure to environmental conditions
  - Estimation of the corresponding insulation resistance change

International Standards for PV modules

IEC 61215 (crystalline silicon), IEC 61646 (thin films)

Requirements for the design qualification and approval of terrestrial photovoltaic modules suitable for long-term operation in general open air climates

Insulation resistance passing criteria

a) the degradation of maximum output power does not exceed the prescribed limit after each test nor 8 % after each test sequence;

b) no sample has exhibited any open circuit during the tests;

c) there is no visual evidence of a major defect, as defined in Clause 7;

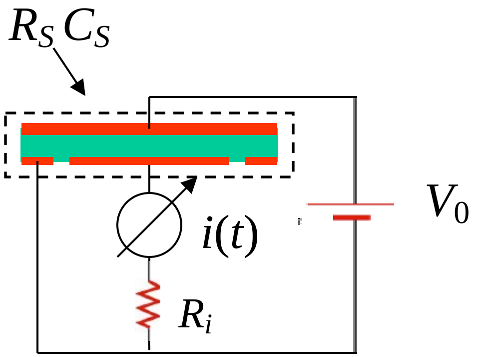
d) the insulation test requirements are met after the tests;
R >= 400 MΩ if area < 0.1 m^2, Dielectric withstanding voltage 1000 V for 1min
R *area >= 40 MΩ m^2 at 500 V if area > 0.1 m^2

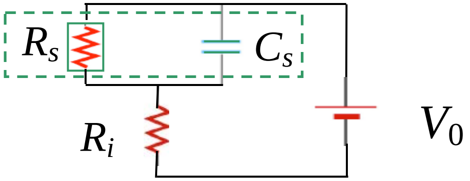
e) the wet leakage current test requirements are met at the beginning and the end of each sequence and after the damp heat test;

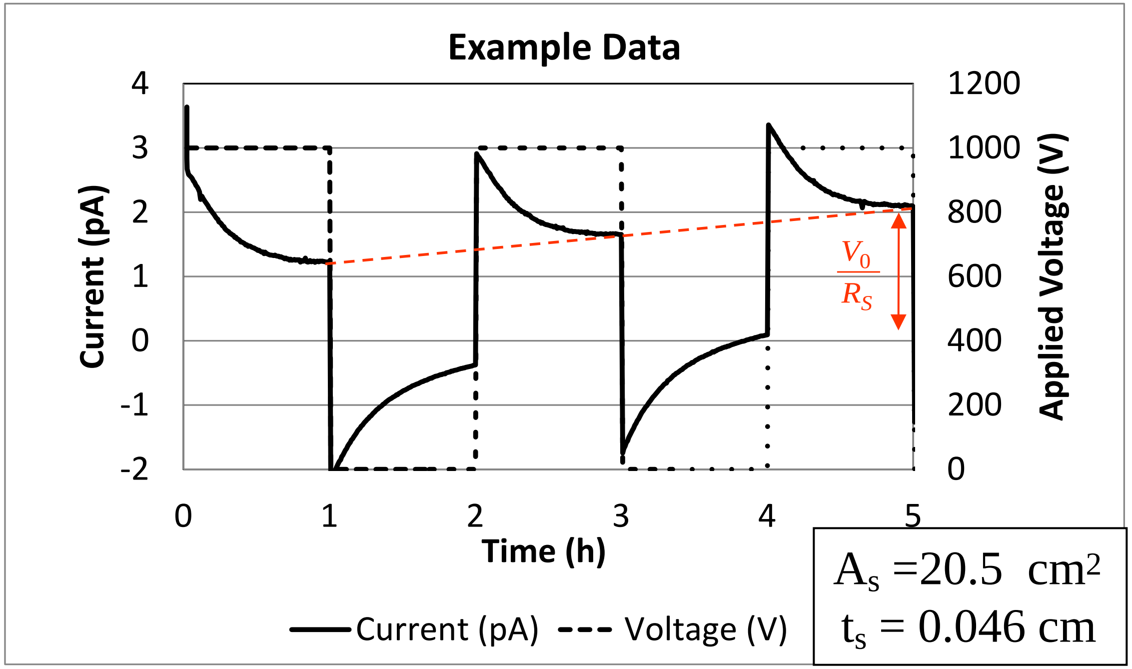
f) specific requirements of the individual tests are met.

HV DC Insulation resistance test (IEC 62788-1-2, 2014)

Step voltage stimulus – current decay response in time domain







A_s =20.5 cm^2
t_s = 0.046 cm

$$R_s >> R_i$$

$$i(t) \approx \frac{V_0}{R_i} e^{-t/R_i C_S} + \boxed{\frac{v_s}{R_S}}$$

transient specimen current

$i_{test} = V_0/R_s \approx 2$pA, $R_s = 10^3$ V/(2 x 10^{-12} A) = 5 x 10^{14} Ω

$\rho = R_s A_s / t_s$ = 2.2 x 10^{17} Ωcm

$R_{s\text{-field}}$ (0.1 m^2) = 2.2 x 10^{17} Ωcm *0.046 cm /10^3 cm^2 ≈ 10^{13}Ω

ρ_{min} ($R_{s\text{-min-field}}$ = 4 x 10^8 Ω,) ≈ 8.6 x 10^{12} Ωcm

$(V_0/R_s)_{max\text{-test}}$ ≈ 5 x 10^{-8} A,

will get there in about 1.3 10^5 cycles, if linear conditions stay

HV Direct Current Insulation Resistance Test

Step voltage stimulus – current decay response in time domain

Pros:

- Simple instrumentation, easy visualization
- Widely accepted
- Large data base of performance (failure rate) in commercial applications (oldest standards , R. Bartnikas, 1982)

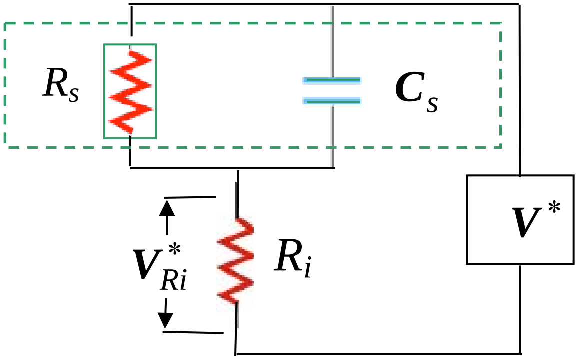
Cons:

- Long testing (electrification) time to read the steady state leakage current $i_{S-\infty} = V_0/R_s$
- Arbitrary acceptance criteria, often based on historic performance (R> 400 MΩ)
- All signals are transient until the steady state conditions are reached, then $v_s = V_0$
- Test results are difficult to link with the physical mechanism of aging and reliability projection
  (the current decay and kinetics of charging are consequence of several processes acting simultaneously: dipolar polarization, charge transport, space charge)

Alternating Current (AC) Insulation Resistance Test

Sinusoidal voltage stimulus – alternating current response at single frequency

Z_S^* –complex impedance

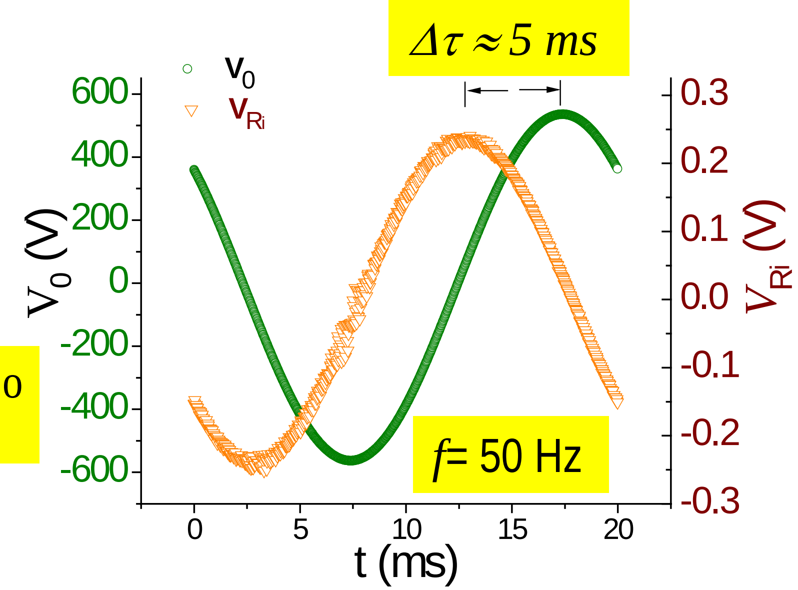


in time domain

$$v(t) = V_0\, \mathbf{sin}(\omega t)$$

$$i(t) = \frac{V_0}{R_i}\, \mathbf{sin}(\omega t + \varphi)$$

$$\varphi = 2\pi\, f\Delta\tau \approx -89.5^0$$



φ= -90° real (ideal) capacitance

0> φ >-90° complex cap with loss (Z_S*)

φ = 0 real impedance , $Z_S = R_s$

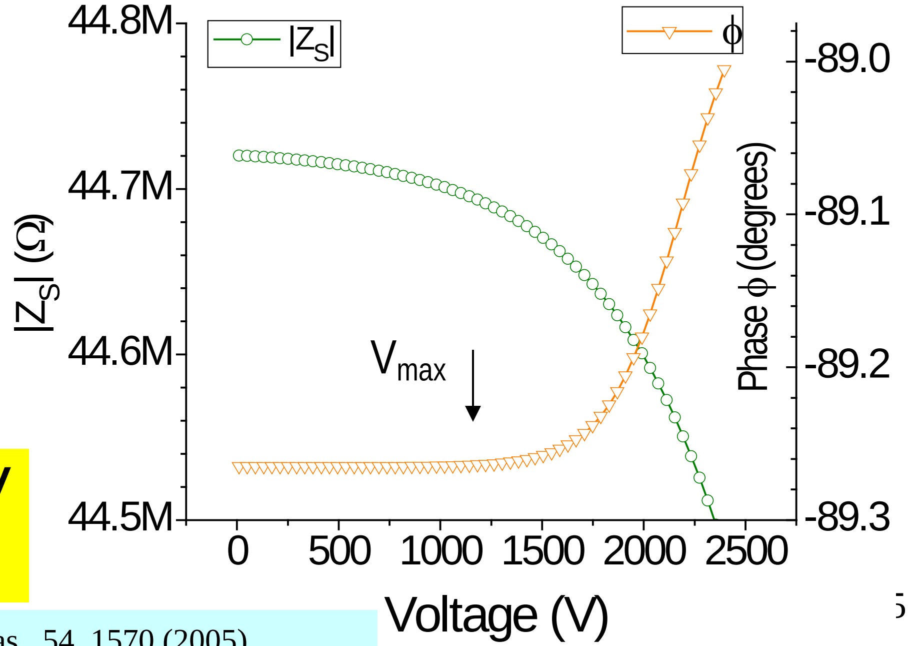
In frequency domain

$$V^* = V_0\, \mathbf{exp}(\, j(\omega t + \varphi))$$

$$Z_S^* = R_\mathrm{i}\left(\frac{V^*}{V^*_{Ri}} - 1\right) \qquad \frac{1}{R_S} \approx \frac{1}{\left|Z_S^*\right|}\left(1 - \mathbf{sin}(|\varphi|)\right)$$

Withstanding voltage V_{max} ≈ 1.2 kV

$R_S = 5.2 \times 10^{11}\ \Omega$

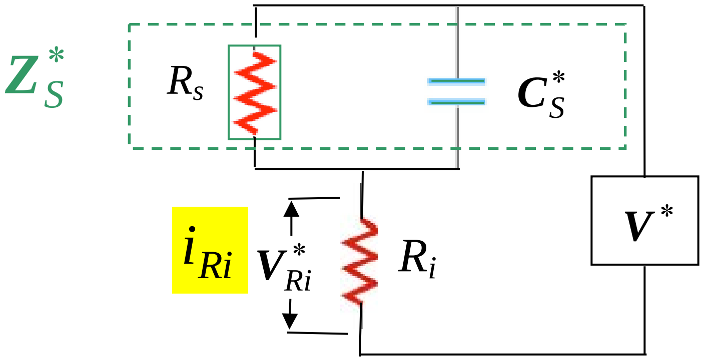


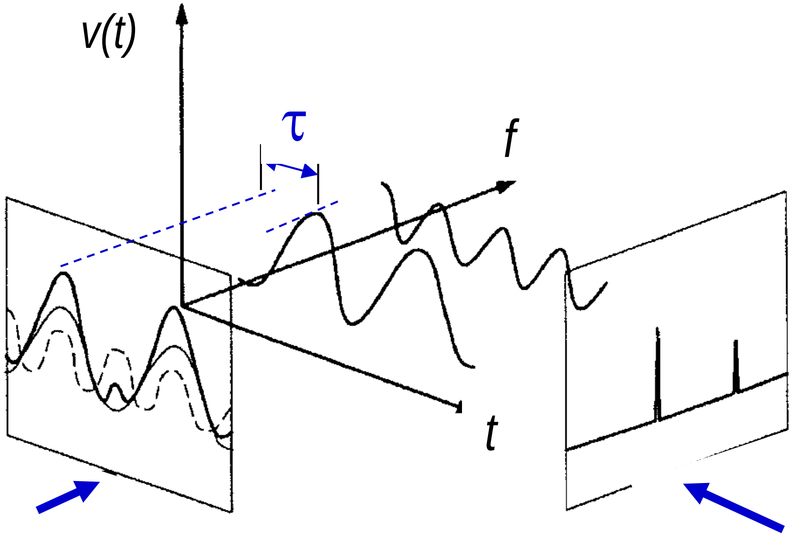
J. Obrzut, IEEE Trans. Instr Meas., 54, 1570 (2005)

Waveform Measurements in Time and Frequency Domain

Complex conductivity σ* in frequency domain

$$i_{Ri} = i_{DC} + i_{\varepsilon''} + i_c$$





Time domain
v(t) = *V*$_0$ *sin* ($\omega t+\phi$)

V$_0$ - amplitude
$\varphi = \omega\tau$ - phase

Freq. domain
$V^* = V_0 e^{i(\omega t+\varphi)}$

$$\sigma^* = \frac{t}{Z_S^* A} = \sigma' + j\sigma''$$

$$1/Z_S^* = Y_S^* = 1/R_S + j\omega C_S^*$$

$$\sigma^* = \sigma_0 + j\omega\varepsilon_0\,\varepsilon^*$$

$$\sigma' = \overset{i_{DC}}{\sigma_0} + \omega\varepsilon_0\varepsilon_r'' \leftarrow i_{\varepsilon''}$$

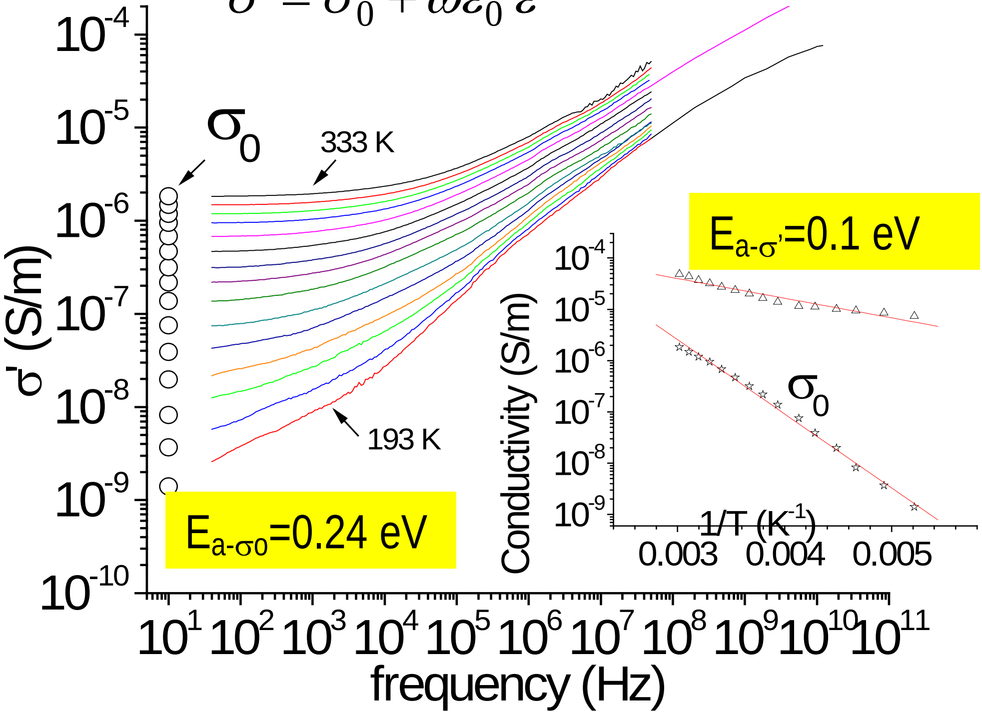
$$\sigma'' = j\omega\varepsilon_0\varepsilon_r' \leftarrow i_c$$

- Time domain - transient response, visualization
- Frequency domain - steady state phasor transforms are convenient for calculating materials property from complex conductivity
- Non-linear response – harmonics
  early indicator of dielectric-breakdown

J. Obrzut, IEEE Trans. Instr Meas., 54, 1570 (2005)

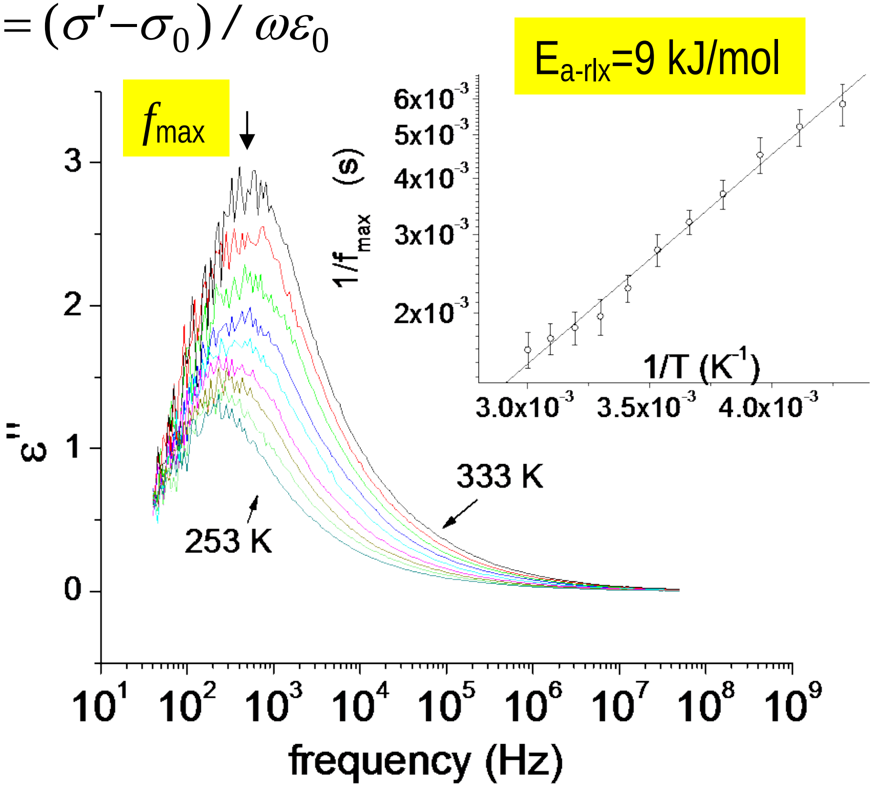
Example of AC conductivity (σ') and dielectric relaxation (ε'') scaling with frequency and temperature

$$\sigma' = \sigma_0 + \omega\varepsilon_0\,\varepsilon''$$



Dielectric relaxation / Arhenius plot

$$\varepsilon'' = (\sigma' - \sigma_0)\,/\,\omega\varepsilon_0$$



$\sigma_0 \leq \sigma'$; $\sigma'(\omega) \rightarrow \sigma_0$ $\omega \rightarrow 0 = \sigma_{DC}$;

universal scaling law $\sigma'(\omega) - \sigma_0 \sim \omega^{n}$:

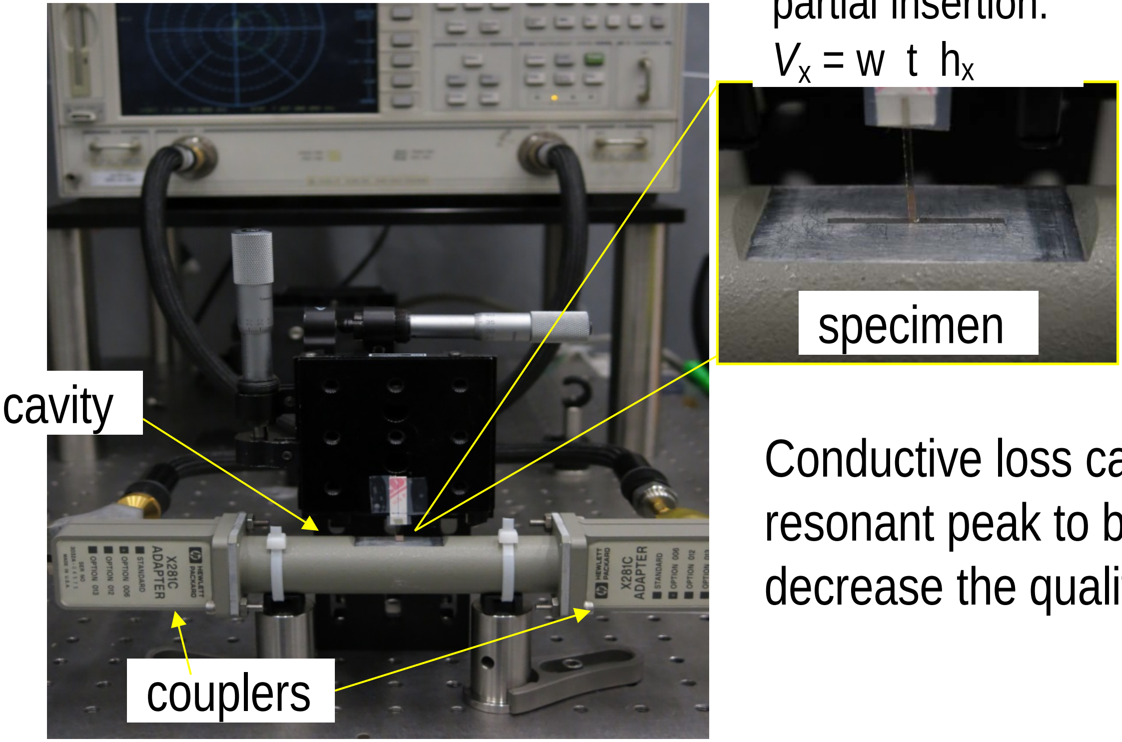
Change in $E_{a\text{-}\sigma 0}$, $E_{a\text{-}\sigma'}$, $E_{a\text{-rlx}}$, ε''_{max} , f_{max} and *exponent n* can be used to determine physical mechanism of aging

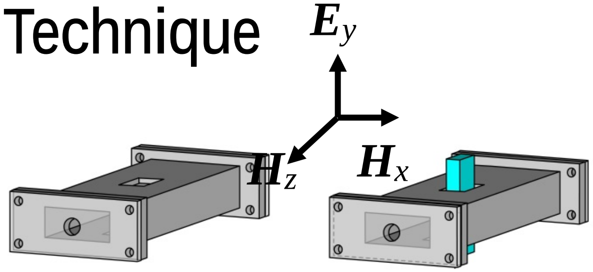
J. Obrzut, Phys.Rev. B, 76, 195420 (2007), Phys.Rev. B, 80, 195211 (2009)

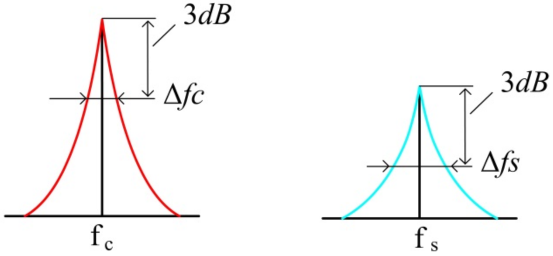
Non Contact Measurement of AC Conductivity by the Microwave Resonant Cavity Technique

partial insertion:

$V_x = w\ t\ h_x$



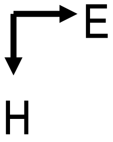




Conductive loss causes the resonant peak to broaden and decrease the quality factor Q.

$$Q = \frac{f_{peak}}{\Delta f}$$

Couplers rotated 89° (cross-polarized) create impedance termination



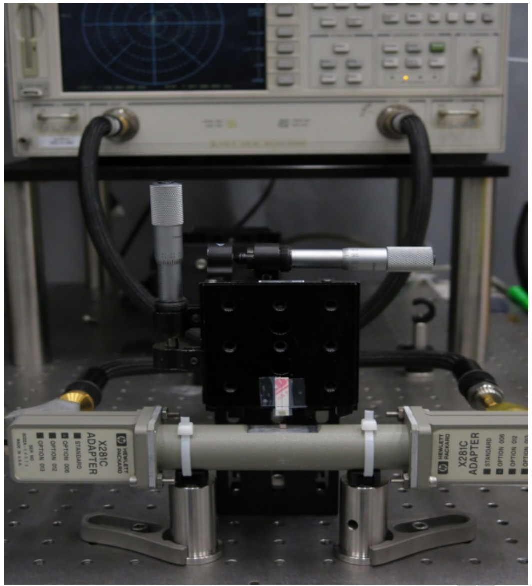
Frequency shift in position of the resonant peak is proportional to the specimen dielectric constant.

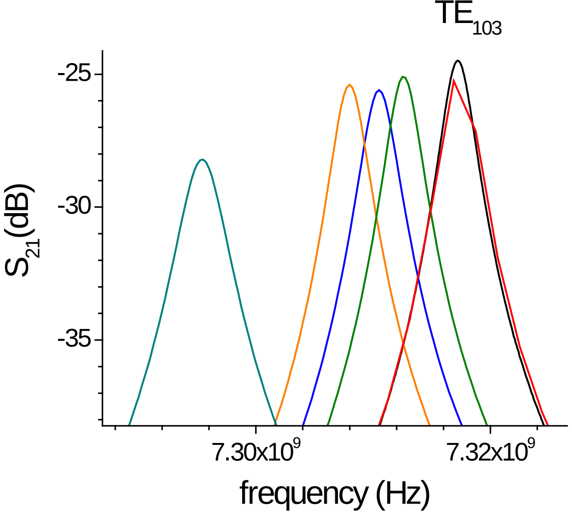
$$\frac{f_c - f_s}{f_c}$$

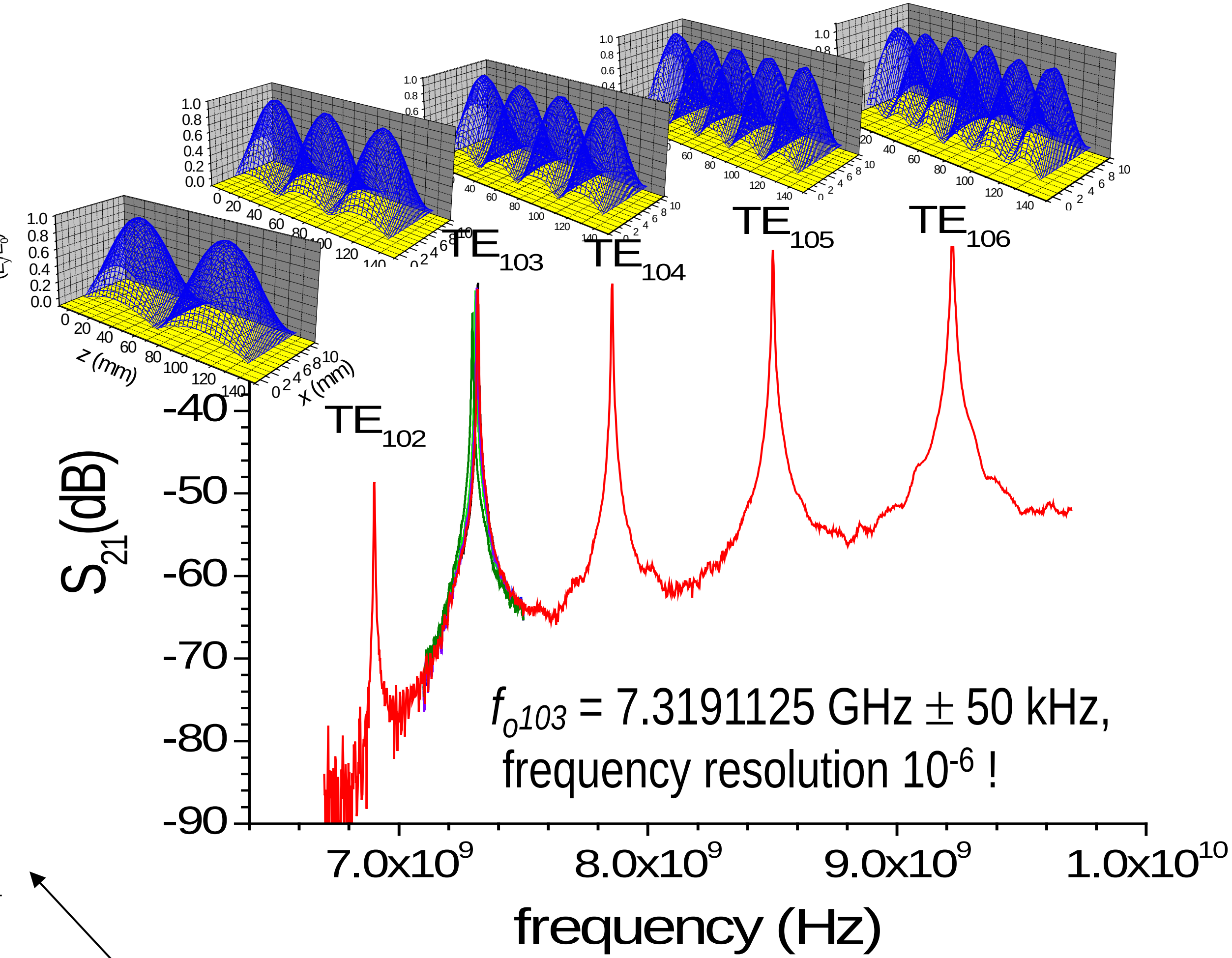
The specimen conductivity and permittivity can be determined from the measured change in Q-factor and frequency shift.

IEC TS 62607-6-4 “Graphene – Surface conductance measurement using resonant cavity” J. Obrzut 2015

Non Contact Measurement of Conductivity by the Microwave Resonant Cavity Technique



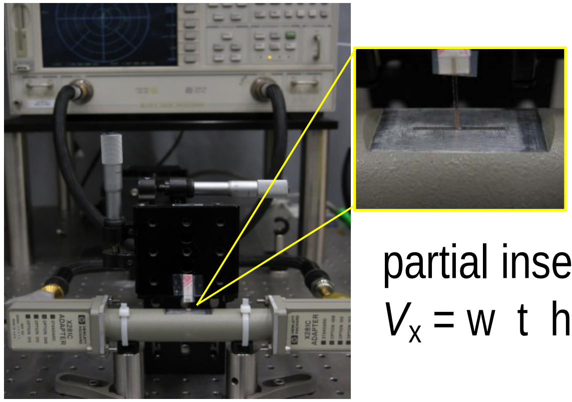




f_{o103} = 7.3191125 GHz ± 50 kHz,
frequency resolution 10^{-6} !

small changes in the specimen conductivity can be easily detected

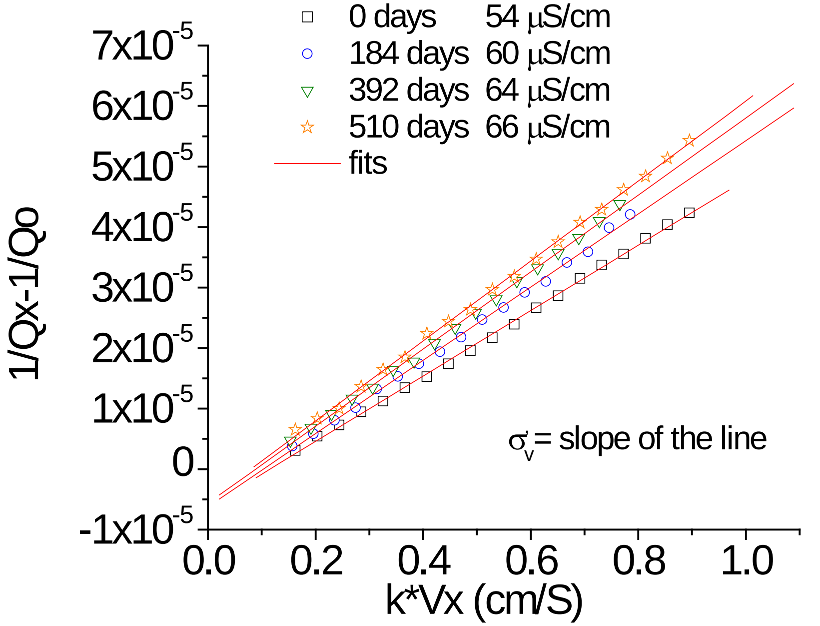
Effect of environmental exposure on MW conductivity of PET (ambient RH, T, sunlight exposure)

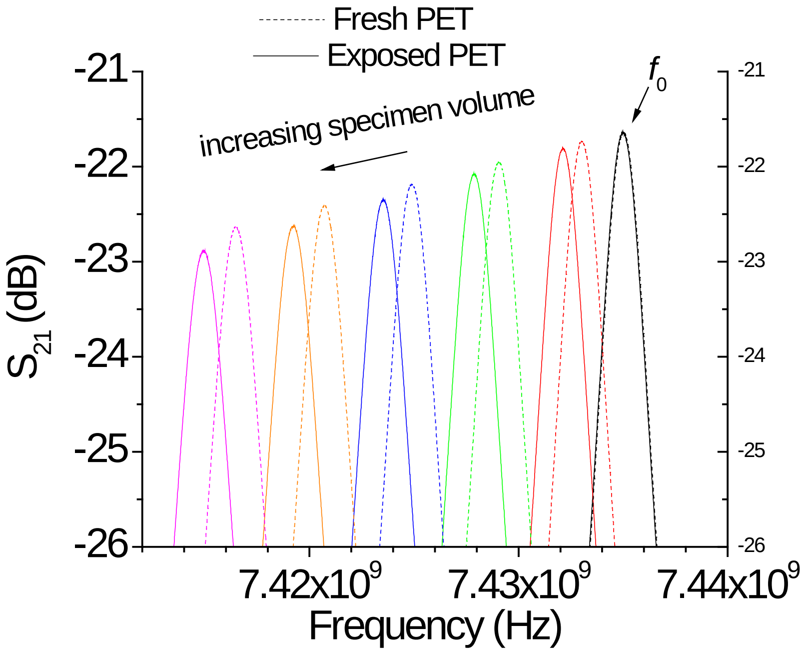


partial insertion:
$V_x = w\ t\ h_x$

Specimen size:
5 mm × 295 µm × 10 mm

$$\frac{1}{Q_x}-\frac{1}{Q_0}=\sigma_v\frac{2}{\pi\varepsilon_0 f_0 V_0}V_x-2b_q \qquad \text{(Eq. 1)}$$





- MW Conductivity increases with duration of the environmental stress
- DC conductivity too small to measure

IEC TS 62607-6-4 "Graphene – Surface conductance measurement using resonant cavity" J. Obrzut 2015

Effect of environmental exposure on MW conductivity of PET

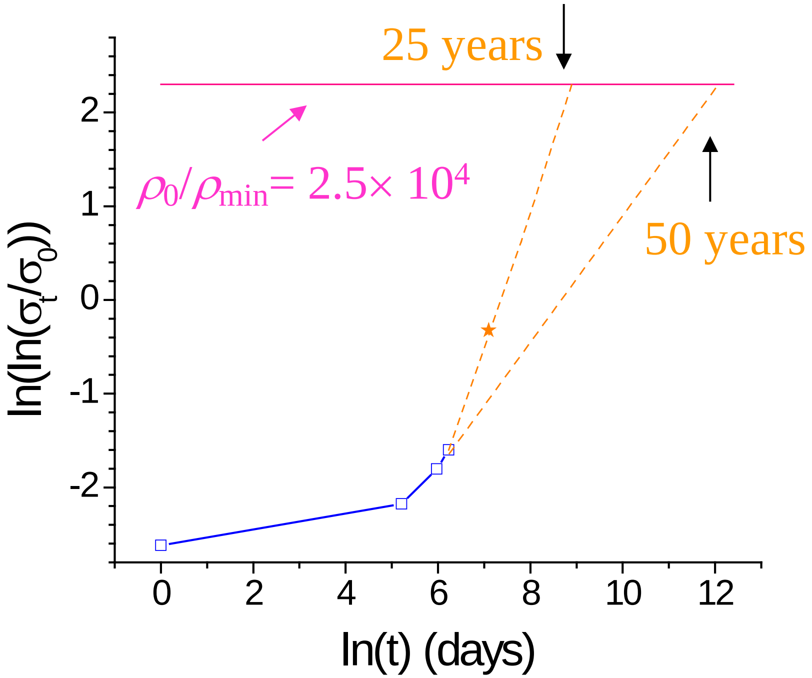
AC (7GHz) conductivity increase

Days	σ (μS/cm)	σ_τ/σ_0
0	54	1
184	60	1.11
392	63	1.16
510	66	1.22
τ_{failure}	1.4 S/cm	2.5 x10^4

Projected degradation of HV DC resistivity

Days	ρ (Ω cm)
0	2.2×10^{17}
184	2.0×10^{17}
392	1.9×10^{17}
510	1.8×10^{17}
τ_{failure}	8.6×10^{12}

$$(R_{\text{s-min-field}} = 4 \text{ x } 10^8 \ \Omega, \ ) \approx 8.6 \text{ x } 10^{12} \ \Omega\text{cm}$$

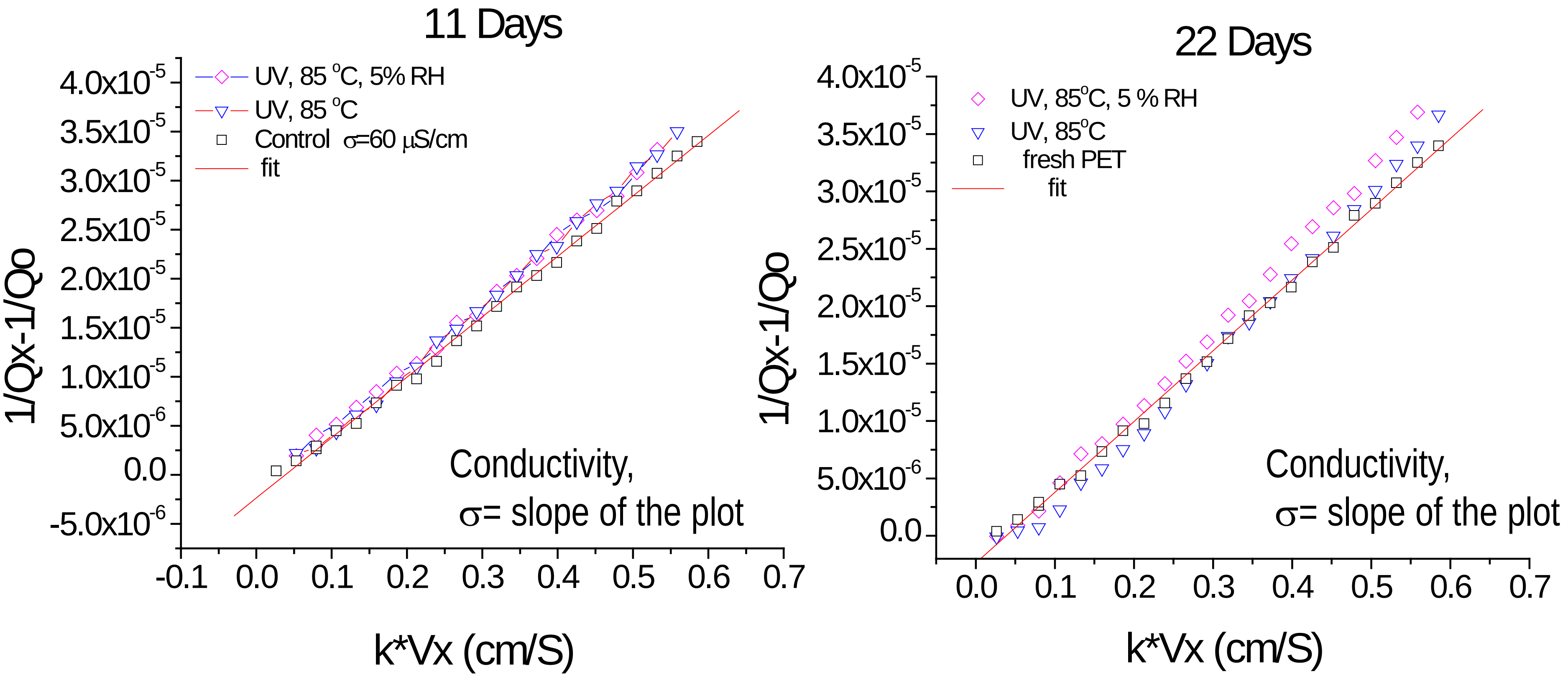


HV DC Insulation resistance test
(per IEC 62788-1-2, 2014)

There is no indication that the environmental exposure would compromise HV DC insulation resistance minimum requirements

MW Conductivity of PET, after UV and Temp accelerated stress test

Measurement: Plots of Quality factor change in conductivity notation (Eq. 1)



11 Days

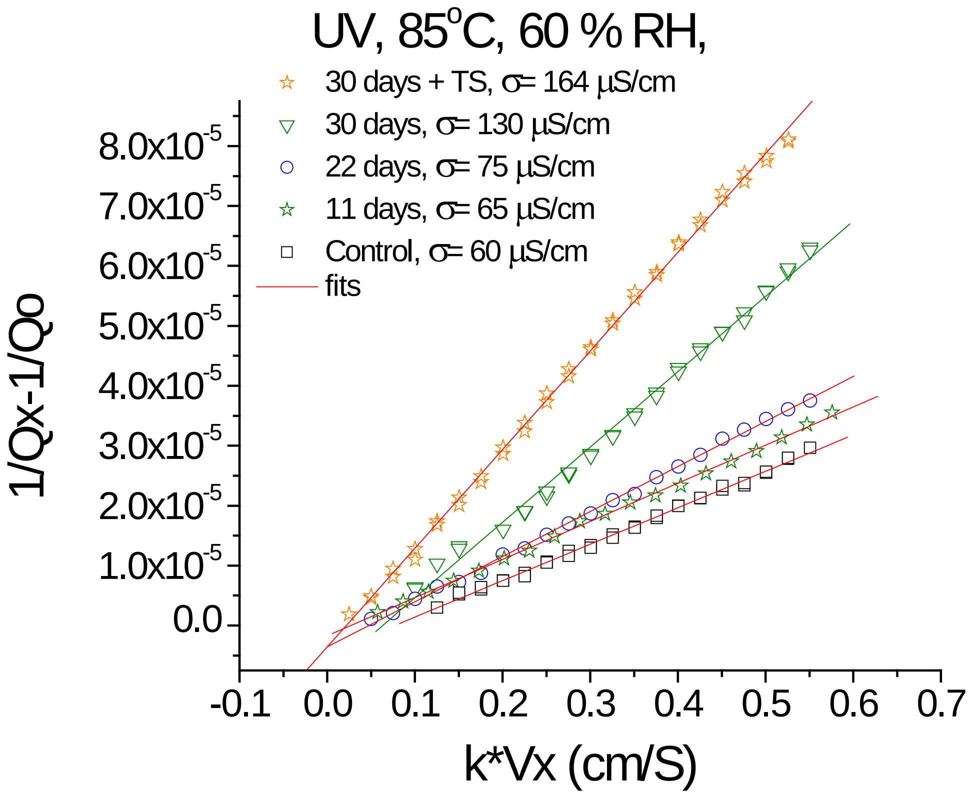
22 Days

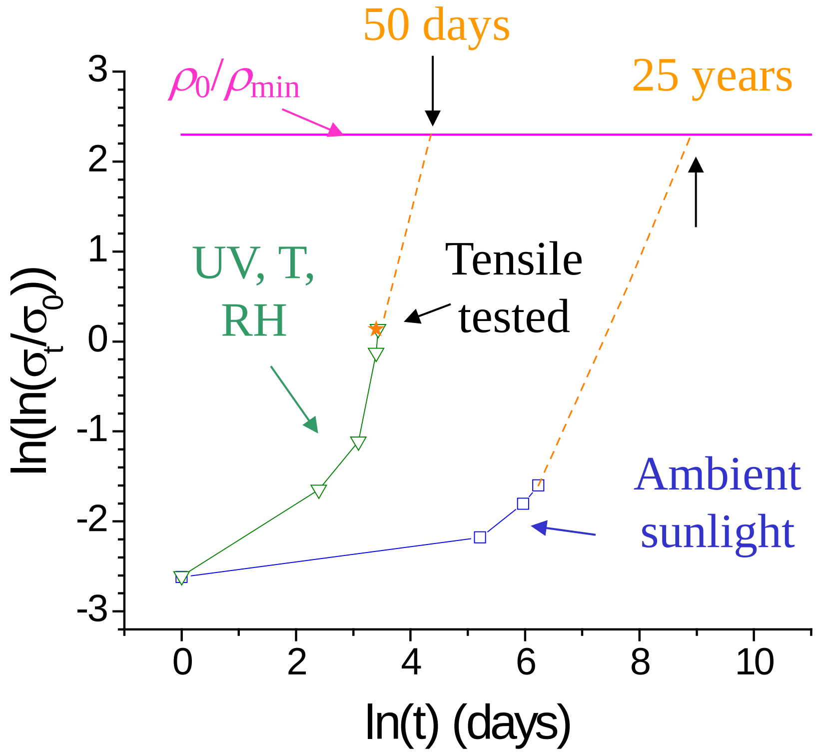
Conductivity,
σ= slope of the plot

Conductivity,
σ= slope of the plot

Conductivity of PET samples increases after the stress, but at low RH level the effect of UV and Temp is not that significant

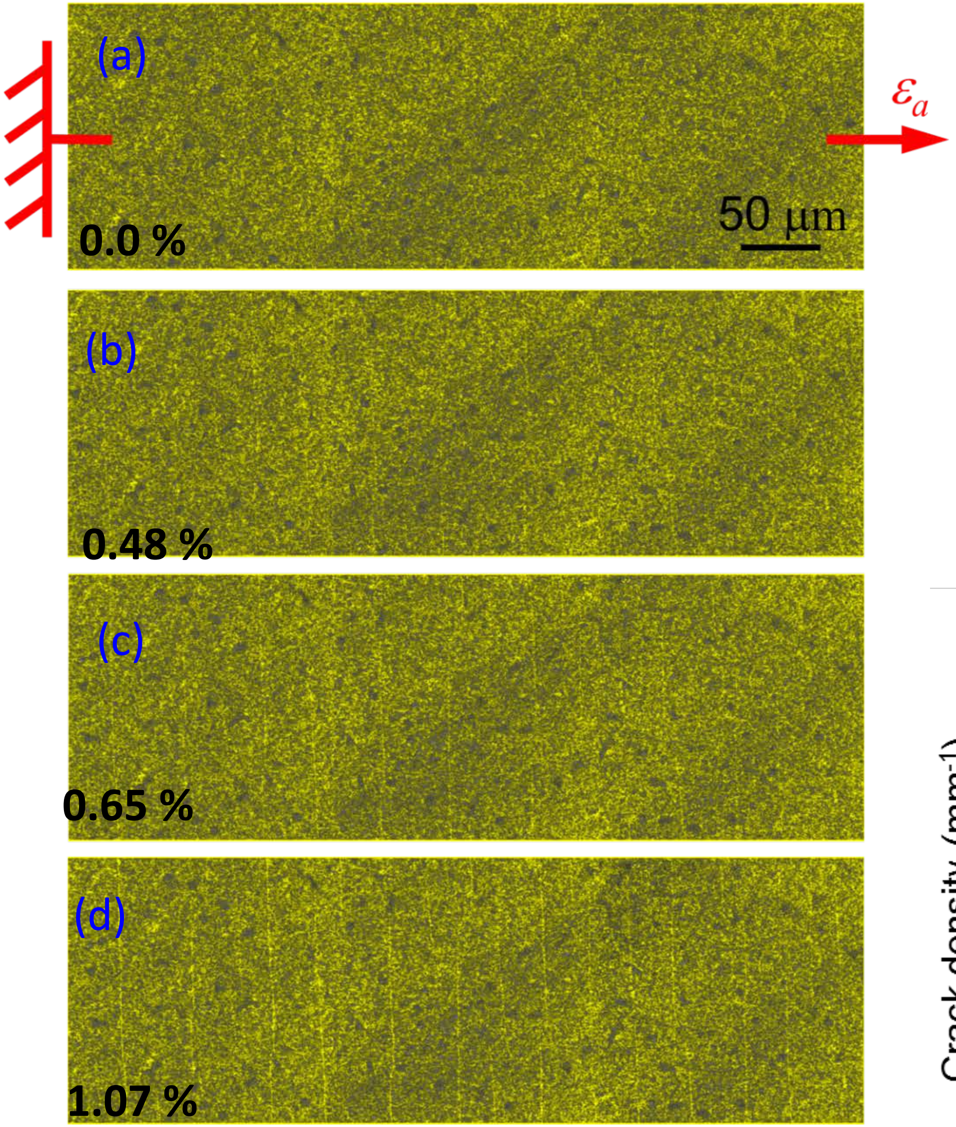
MW Conductivity of PET, after exposure to UV, Temp and 60% RH

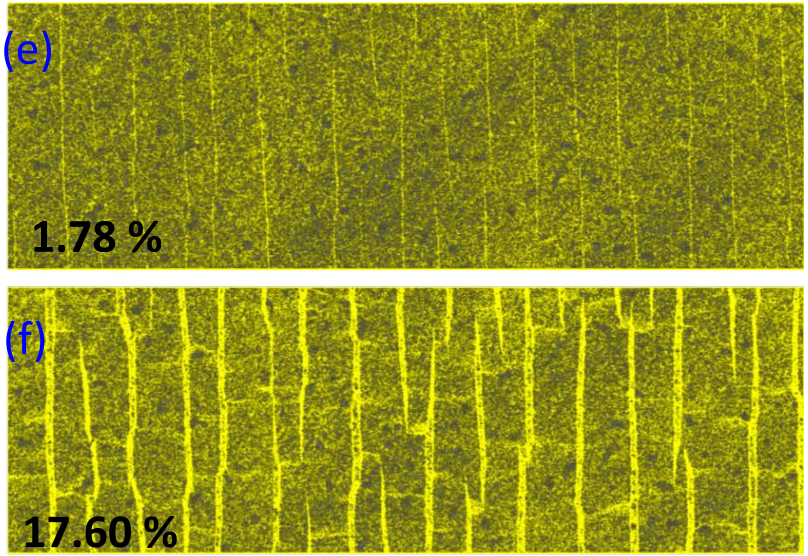


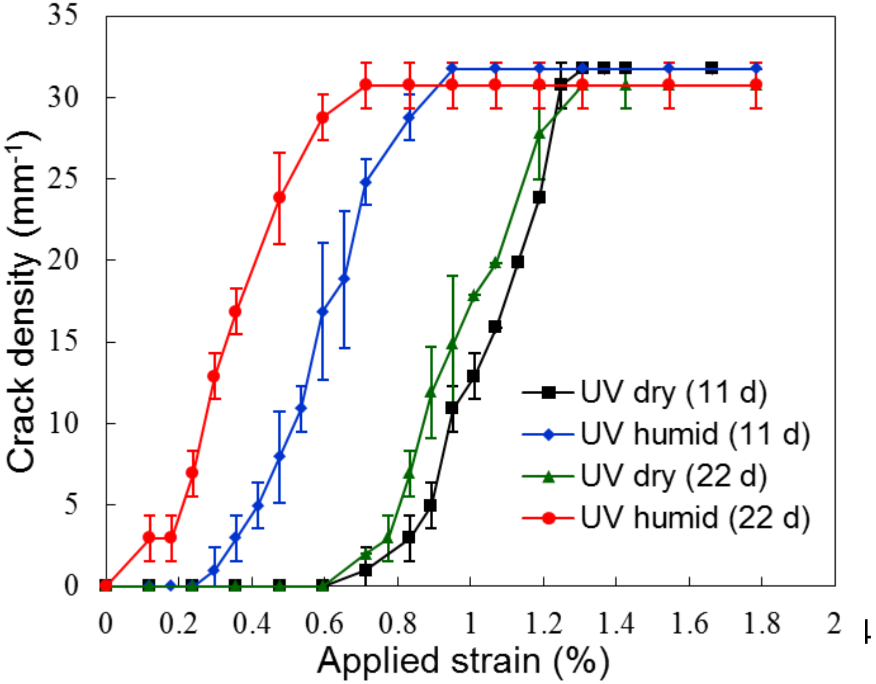


Under UV, Temp stress conditions Humidity dramatically accelerate loss of insulation resistance. Mechanical elongation creates additional conducting paths.

Tensile test results







Crack density increases with RH

Summary

- Direct Current (DC) High Voltage Insulation Resistance Test: step voltage – current decay in time domain
  easy to visualize, commonly used

$$R = V_0 / i_R(\tau_\infty) \, ; i_c \, , i_{\varepsilon''} = 0$$

- Alternating Current (AC) Insulation Resistance Test phasor transform in frequency domain

$$\frac{1}{R_S} \approx \frac{1}{\left| \boldsymbol{Z}_S^* \right|} \left(1 - \boldsymbol{sin}(|\varphi|) \right)$$

$$i_{AC}(\omega) = i_R(\omega = 0) + i_{\varepsilon''}(\omega) + i_C(\omega)$$

$$R_{DC} > R_{AC}$$

  fast, physical mechanism of charge transport at high frequencies eliminates ambiguity with ionic current (redox process)

- Demonstrated non-contact resonant cavity test method for conductivity of PET samples. The method operates at 7 GHz and is sensitive to aging effects caused by the UV, T, RH ambient and accelerated stress. No direct correlation with the life test.

- sensitive, fast, non-invasive, small specimens (New IEC std developed at NIST).

Thank you!