Characterization of optical transition-edge sensors

Kaori Hattori

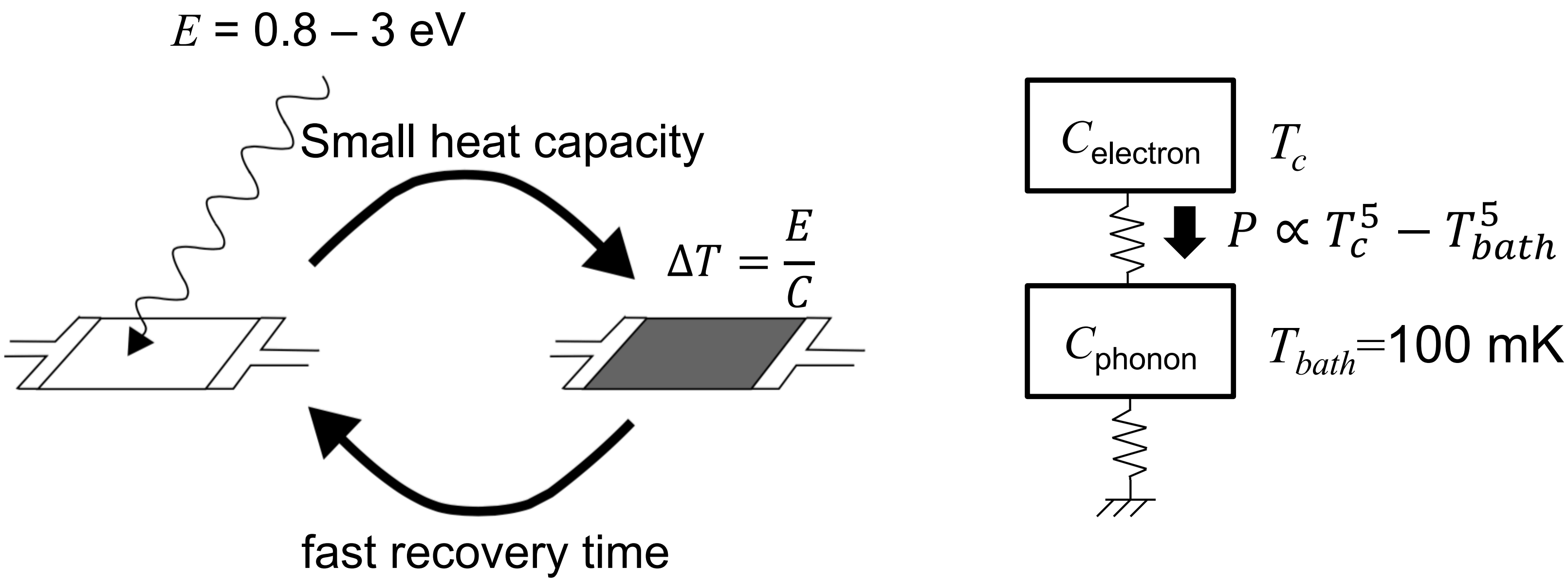
National Institute of Advanced Industrial
Science and Technology (AIST)

Outline

- Optical transition-edge sensor

- Complex impedance of fast TES (0.2 – 5 μs fall-time)
  - Impedance measurements at high frequency (up to 20 MHz)
  - α, β, time constant, and energy resolution

Optical transition-edge sensor



E = 0.8 – 3 eV

Small heat capacity

$\Delta T = \frac{E}{C}$

fast recovery time

C_{electron} T_c

$P \propto T_c^5 - T_{bath}^5$

C_{phonon} T_{bath}=100 mK

- Ti/Au bilayer (20 / 10 nm)
- Small heat capacity : 5 μm× 5 μm
- Fast recovery time : 0.2 μs (T_c = 360 mK), 4 μs (170 mK)
  TES not released - dielectric layer underneath
  Cooled by electron-phonon thermal coupling

Applications

Optical TES can resolve energy and photon number.

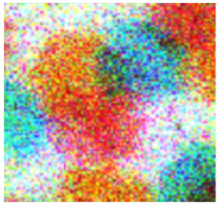
- Quantum information

  Short pulse recovery time and efficiency ~ 100%

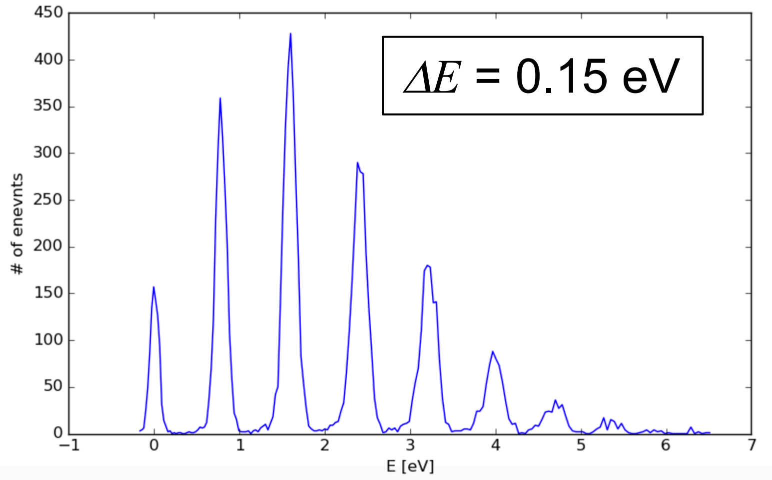
  98±1% at 850 eV D. Fukuda et al., *Opt. Exp.* 19 (2012) 870.
- Biological imaging

  Extremely low dark counts and high energy resolution

Microscopy imaging
Daiji Fukuda, Friday



Niwa et al. *Scientific Reports* **7** (2017) 45660.



Spectrum of pulsed laser

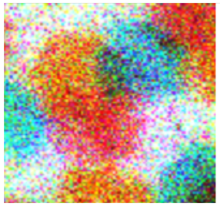
Typically ΔE_{FWHM} = 0.1 - 0.2 eV at 0.8 eV

What limits energy resolution?

Applications – biological imaging

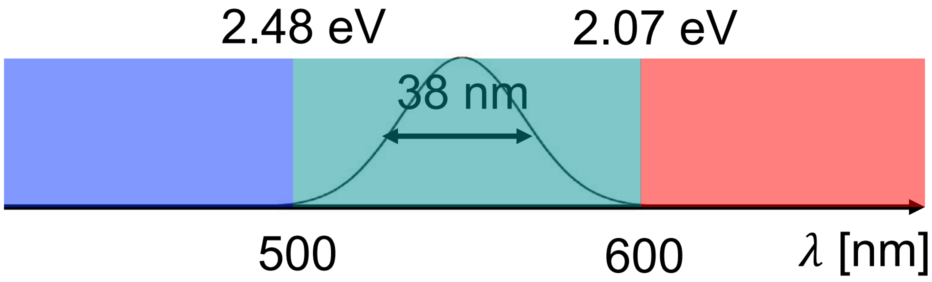
color	red	green	purple
λ [nm]	780	550	380
E [eV]	1.6	2.3	3.3
ΔE [eV]	0.15	0.15	0.15
$\Delta\lambda$ [nm]	75	38	18

Microscopy imaging
Daiji Fukuda, Friday



Niwa et al. *Scientific Reports* **7** (2017) 45660.

Energy resolution ~ constant.
$\Delta\lambda$ increases as wavelength is longer.



RGB imaging is doable.
Significant amount of leakage existing.
Need higher energy resolution.

Energy resolution

Theoretical limit

$$\Delta E = 2.36\sqrt{4k_B T_c^2 C/\alpha \sqrt{n(1+2\beta)/2}}$$

How far is energy resolution of optical TESes from theoretical limit?

Complex impedance

$$Z_{TES}(\omega) = R_{TES}(1+\beta) + \frac{R_{TES}\mathcal{L}}{1-\mathcal{L}}\frac{2+\beta}{1+i\omega\tau_0/(1-\mathcal{L})}$$

Assume simple thermal model ← Optical TES doesn’t have absorber.

Complex impedance

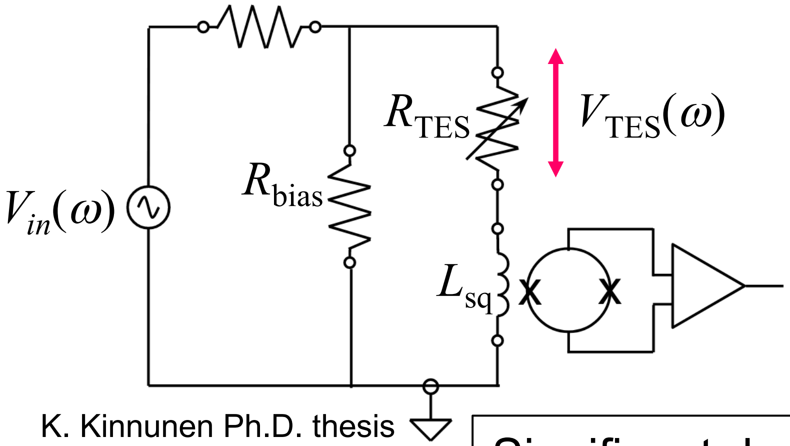
$$Z_{TES}(\omega) = R_{TES}(1+\beta) + \frac{R_{TES}\mathcal{L}}{1-\mathcal{L}}\frac{2+\beta}{1+i\omega\tau_0/(1-\mathcal{L})}$$

Fast response
→ Measure impedance at high frequency

Challenge
→ Parasitic impedance in circuit
→ impedance mismatch
→ hard to build appropriate circuit model

Transfer function

Circuit model



K. Kinnunen Ph.D. thesis

Transfer function

$$V_{\mathrm{TES}}(\omega) = F(\omega)V_{in}(\omega)$$

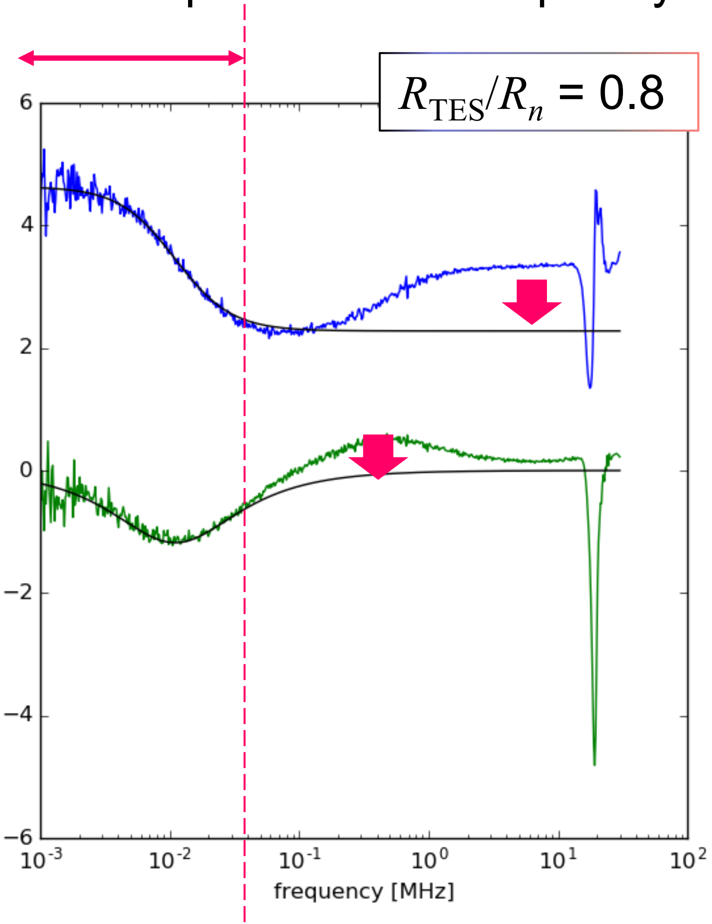
Significant deviation observed above ∼ 1MHz

At $\omega >> 1/\tau_{\mathrm{TES}}$, complex impedance is independent of frequency,

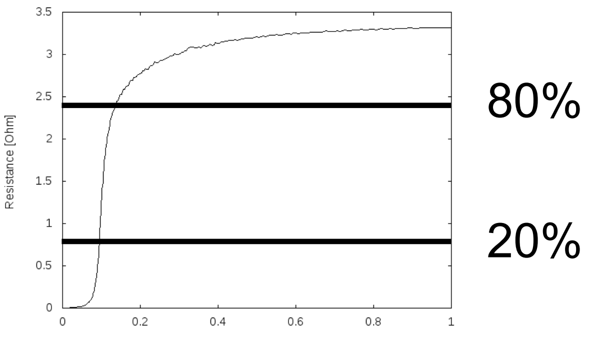
$$Z_{\mathrm{TES}}(\omega \rightarrow \infty) = R_{\mathrm{TES}}(1+\beta).$$

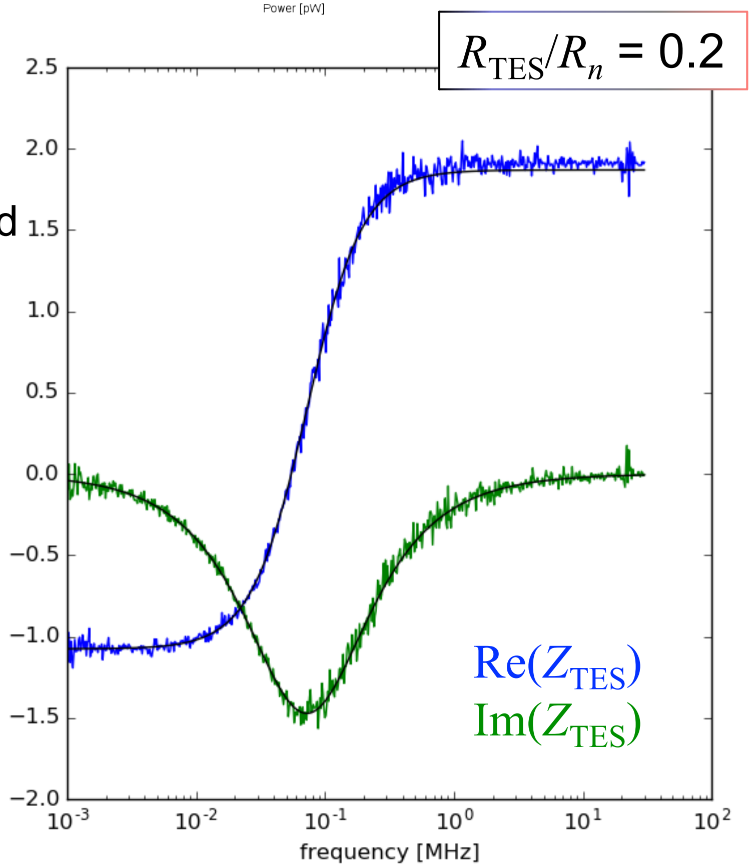
Corrected transfer function at high frequency

At high R_{TES}/R_n where TES is slow,
fit Z_{TES} to $Z_{\mathrm{measured}}(\omega < 0.05\ \mathrm{MHz})$
Use data points at low frequency

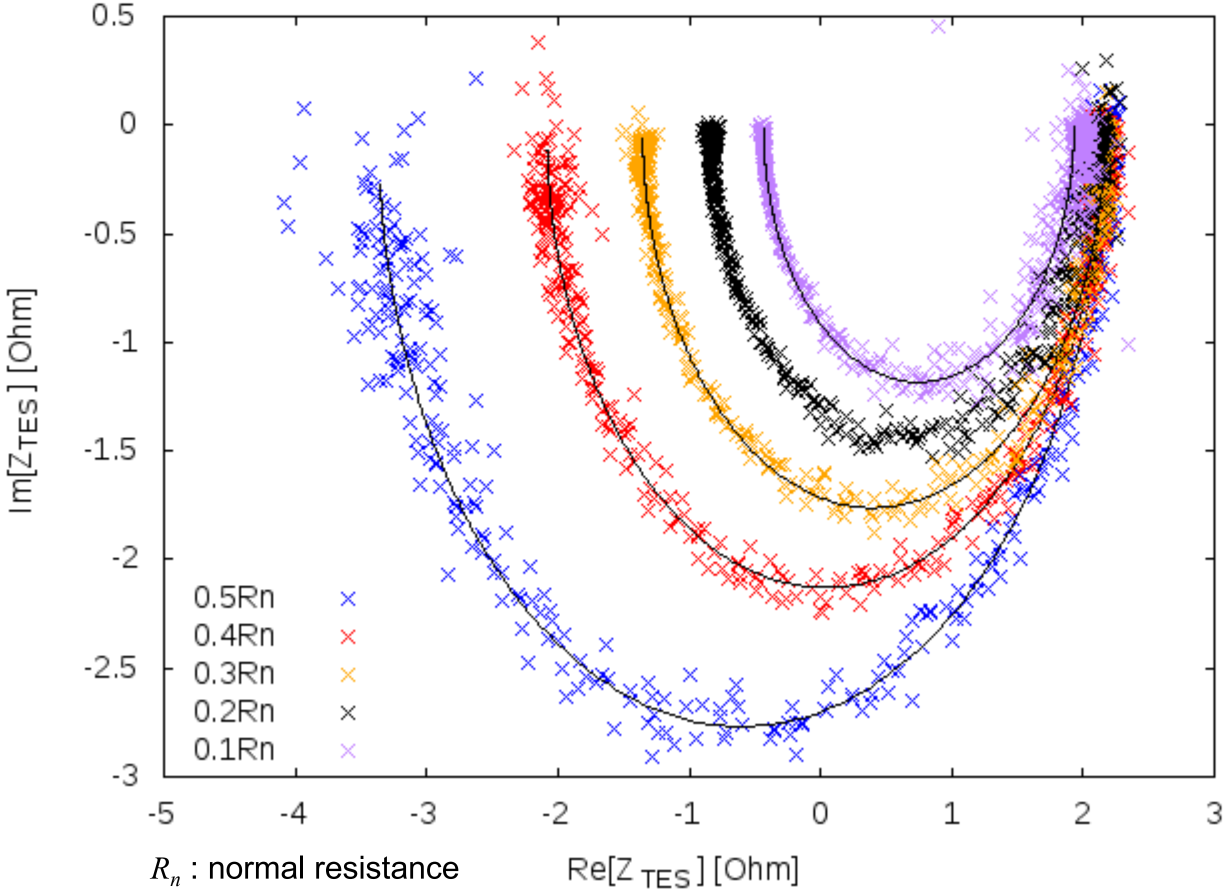


Corrected transfer function





Complex impedance

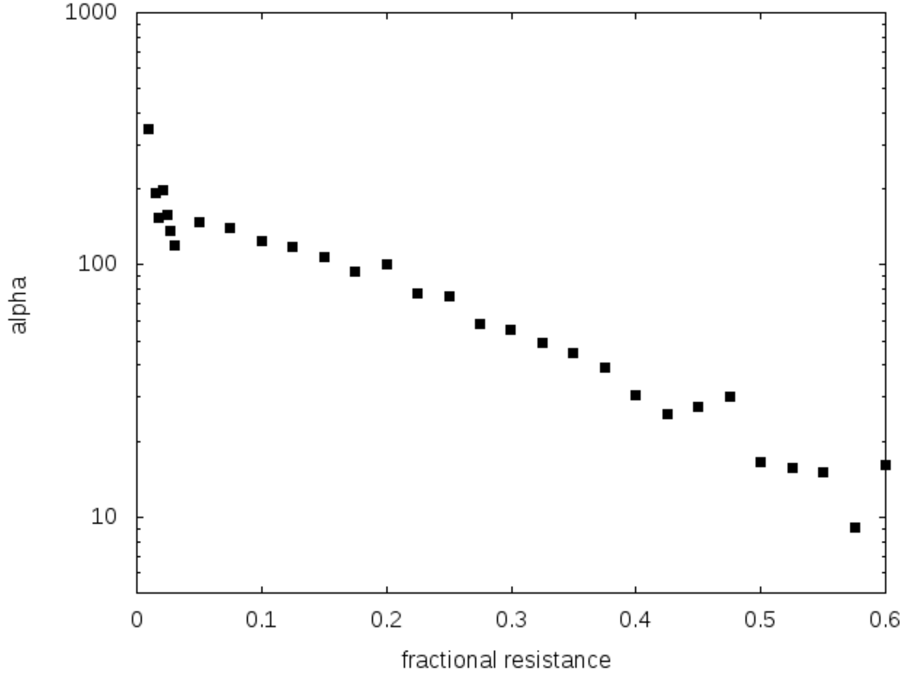


R_n : normal resistance

Temperature / current sensitivity

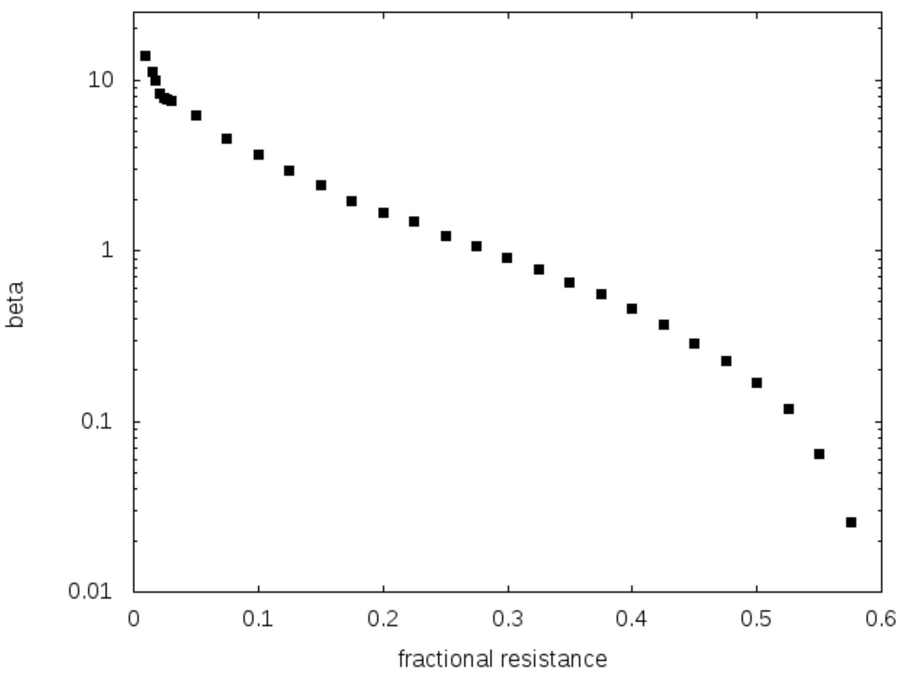
Temperature sensitivity

$$\alpha = \frac{T}{R_{TES}} \frac{\partial R_{TES}}{\partial T}\bigg|_{I}$$

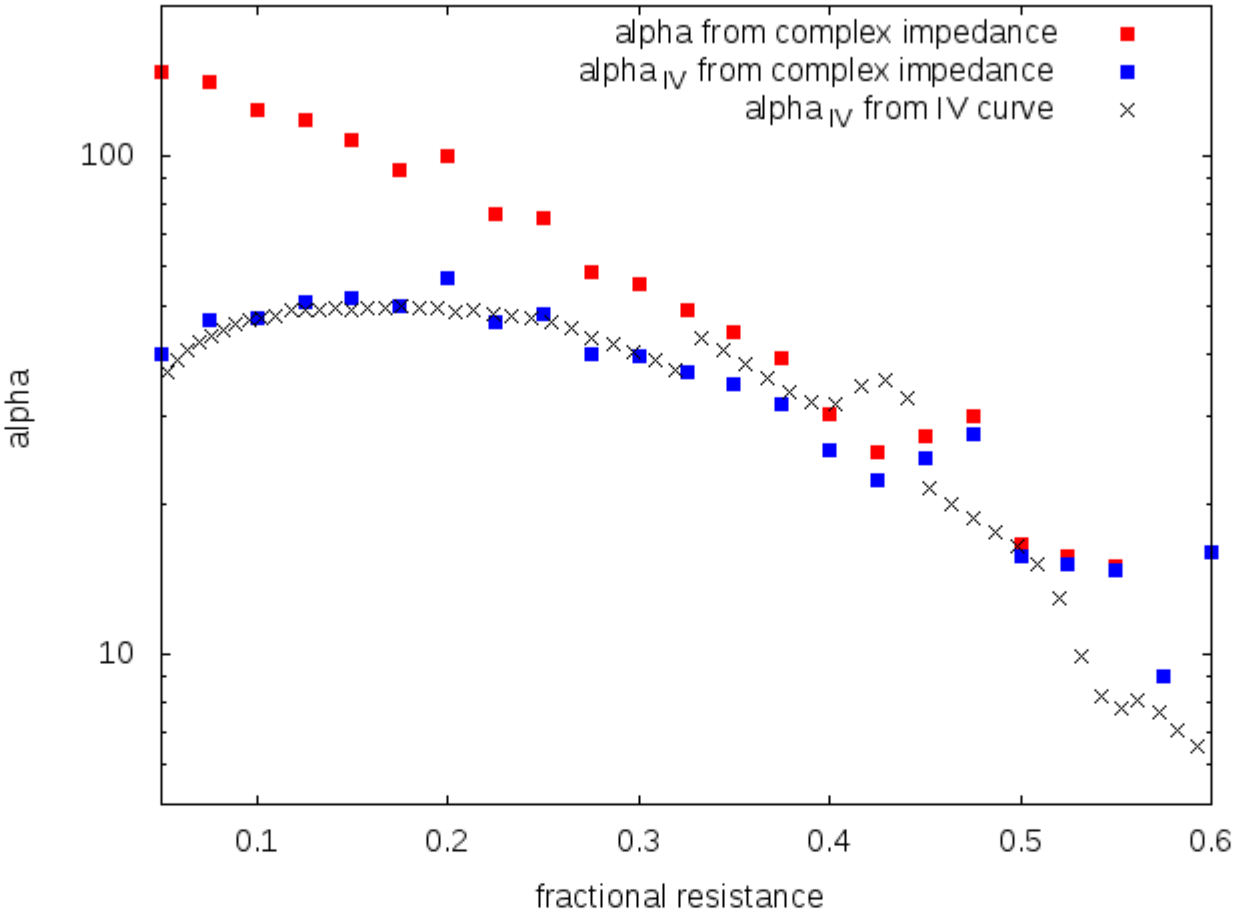


Current sensivity

$$\beta = \frac{I}{R_{TES}} \frac{\partial R_{TES}}{\partial I}\bigg|_{T}$$



Temperature sensitivity



Temperature sensitivity

$$\alpha = \frac{T}{R_{TES}} \frac{\partial R_{TES}}{\partial T}\bigg|_{I=const.}$$

Temperature sensitivity calculated from IV curve

K. Kinnunen Ph.D. thesis

$$\alpha_{IV} = \frac{T}{R_{TES}} \frac{dR_{TES}}{dT}$$

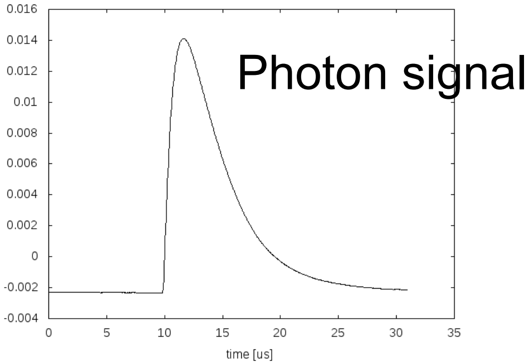
$$= \frac{GT}{P} \frac{\frac{dV}{dI} - R_{TES}}{\frac{dV}{dI} + R_{TES}}$$

$$= \frac{2\alpha + \frac{GT}{P}\beta}{2 + \beta}$$

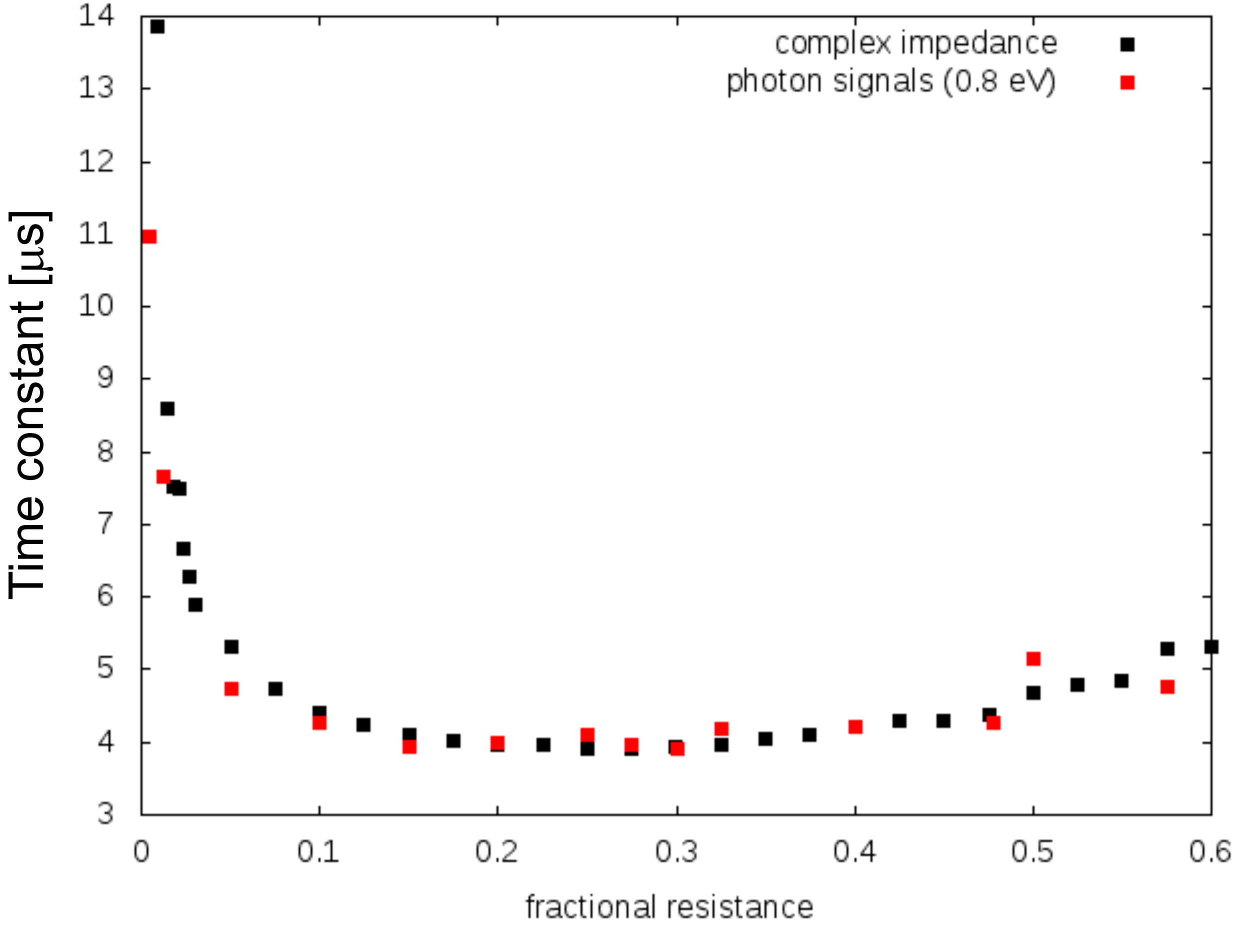
α_{IV} can be calculated from IV curve.

α and β from complex impedance.

Time constant



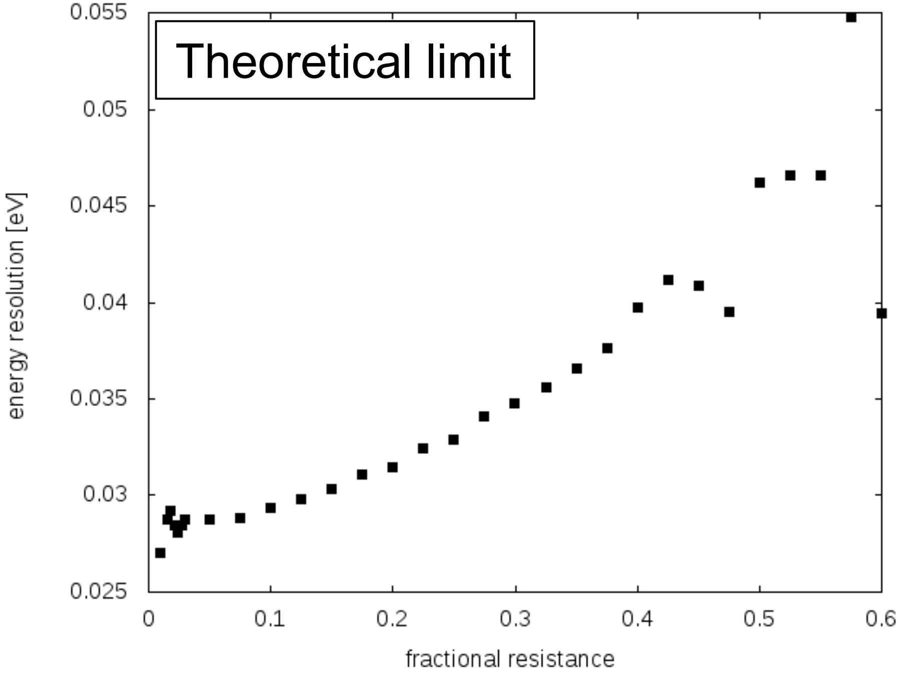
$$\tau_{TES} = \frac{C}{G}\frac{1+\beta+R_{bias}/R_{TES}}{1+\beta+\frac{R_{bias}}{R_{TES}}+(1-\frac{R_{bias}}{R_{TES}})\mathcal{L}}$$

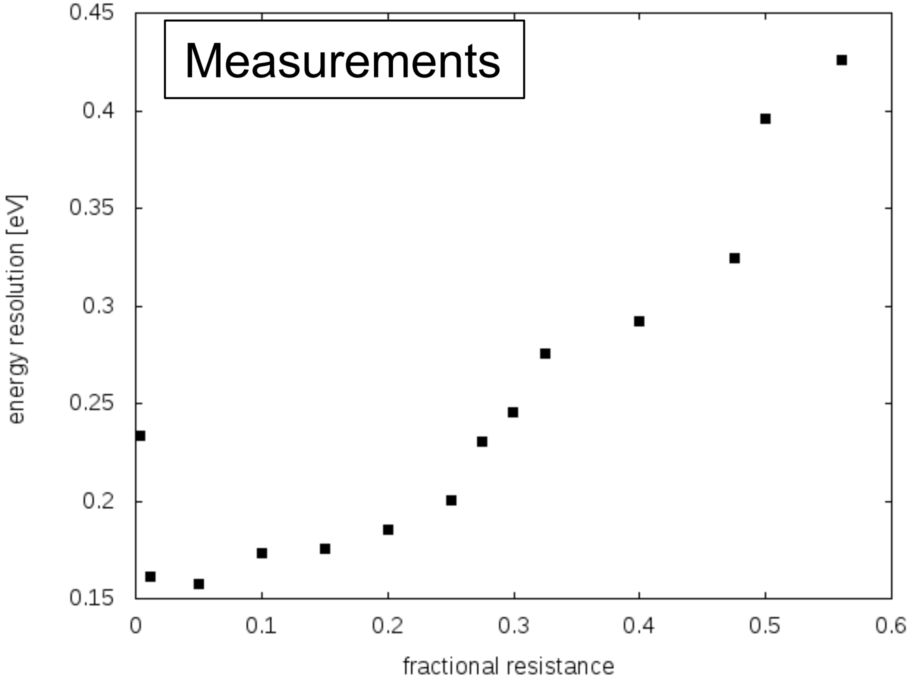


Energy resolution

measurements vs theoretical limit

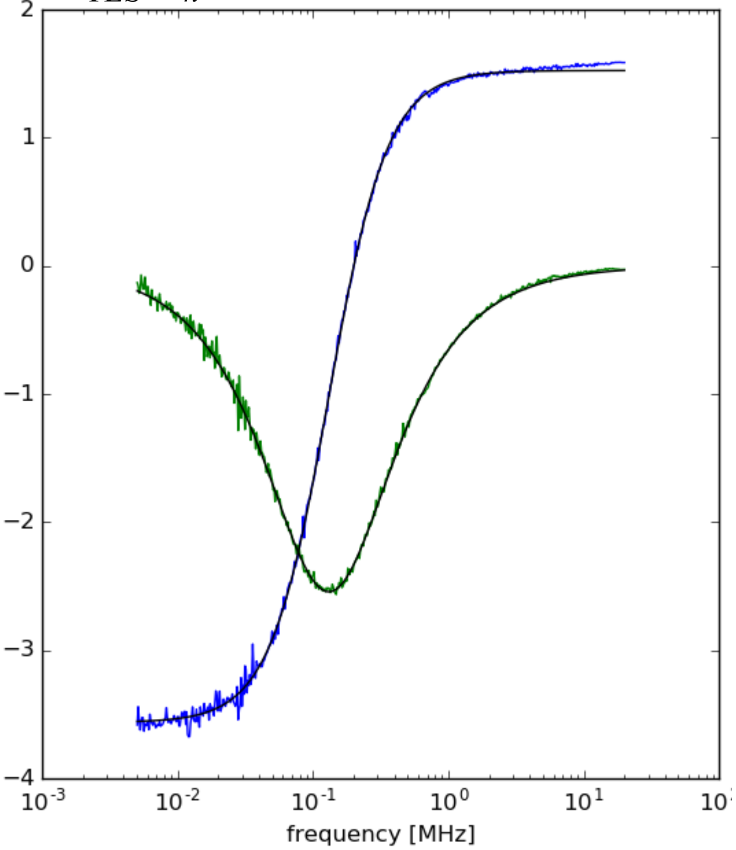
$$\Delta E = 2.36\sqrt{4k_B T_c^2 C/\alpha\,\sqrt{n(1+2\beta)/2}}$$



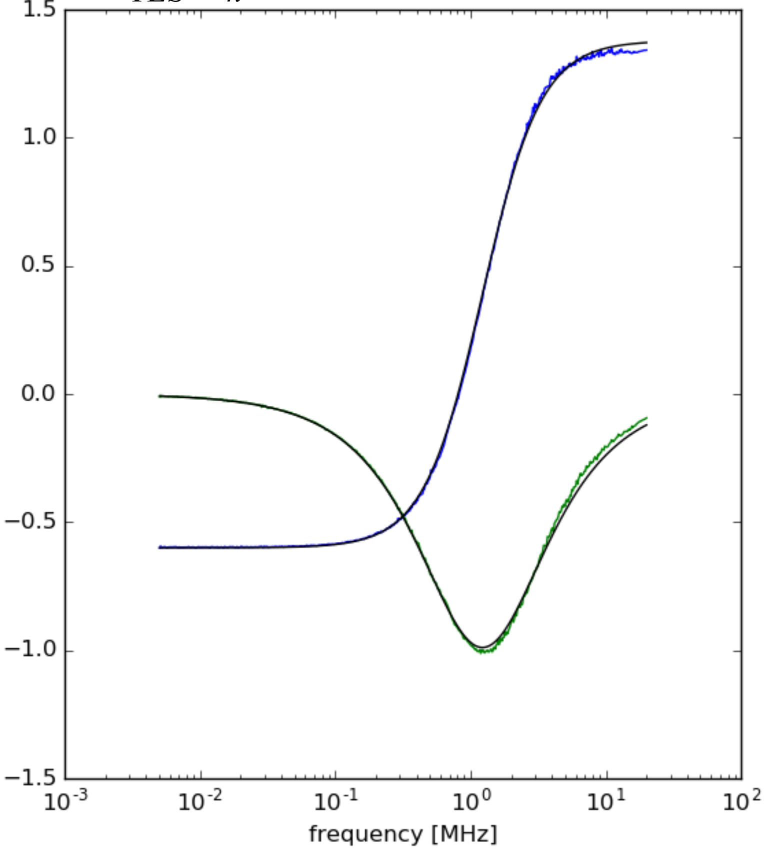


Ultra fast TES

$R_{\mathrm{TES}}/R_n = 65\ \%$



$R_{\mathrm{TES}}/R_n = 25\ \%$



Time constant = 0.2 μs
Significant deviation from simple model at bias point for photon detection (0.1 R_n)

Summary

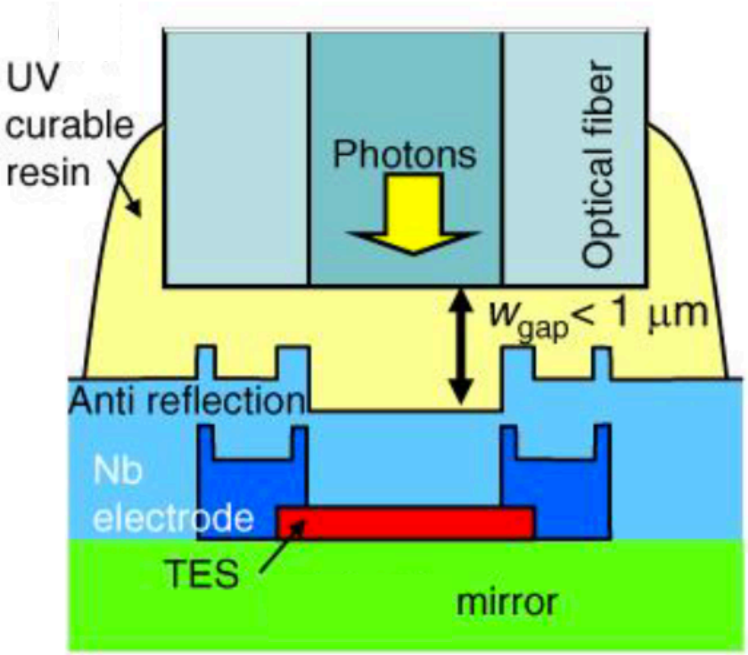
◆ Unique features of optical TES are
  Fast recovery time : 0.2 – 4 μs
  No absorber or additional heat capacity :
    simple thermal model

◆ Complex impedance measurements at high frequency up to 20 MHz
  Showed new correction method
    Agreed with temperature sensitivity calculated from IV curve.
      time constant of photon signals.

◆ Measured $\Delta E \geq 5\times$ theoretical limit.
  We will investigate excess noise.

◆ Ultra fast TES (0.2 μs)
  Need to consider new thermal model

Structure


UV curable resin
Photons
Optical fiber
w_{gap}< 1 µm
Anti reflection
Nb electrode
TES
mirror