SAND2009-3899C

Comparison of thermal conductivity and thermal boundary conductance sensitivities in continuous-wave and ultrashort pulsed thermoreflectance analyses

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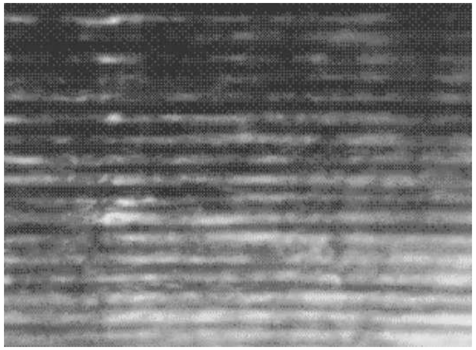
17th Symposium on Thermophysical Properties
Monday, June 22, 2008

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

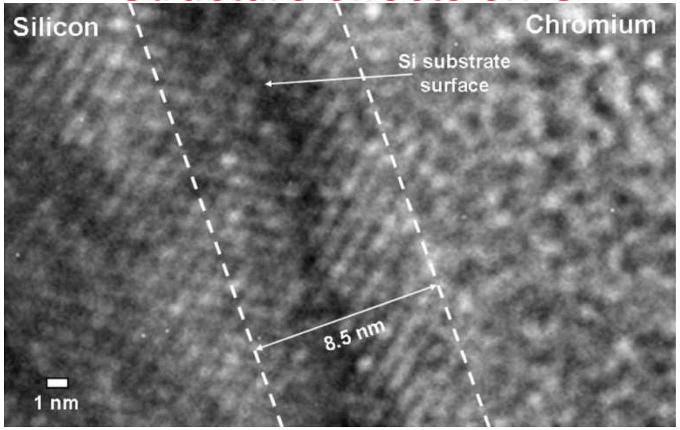
Sensitive measurements of thermal properties of nanostructures

Superlattice structures for TE



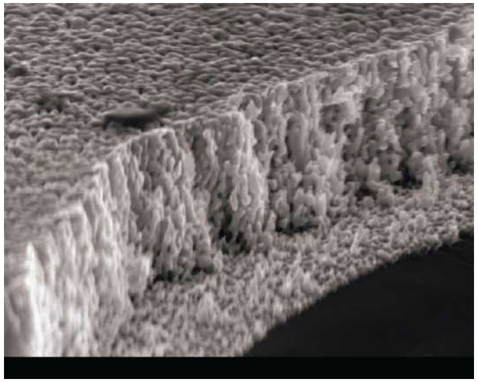
Touzelbaev *et al*., JAP, 90, 763 (2001)

Structure effects on *G*



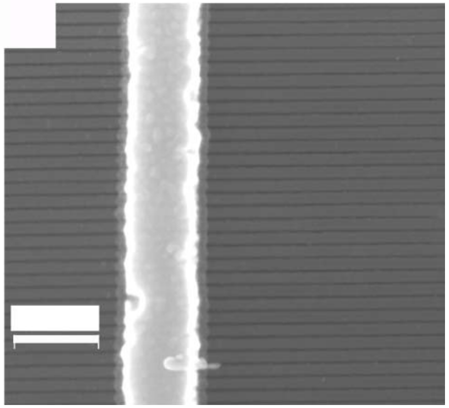
Hopkins *et al*., JHT, 1**30**, 062402 (2008)

Nanoporous films



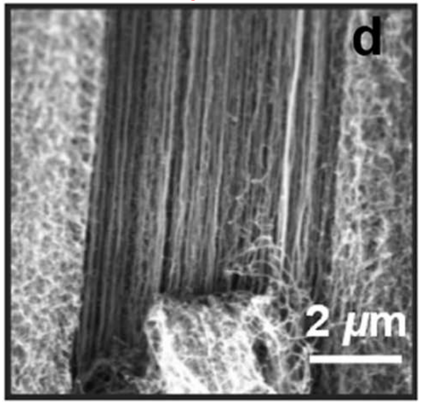
Hopkins *et al*., Journal of Nanomaterials, **2008**, 418050 (2008)

Nanowires



Boukai *et al*., Nature, **451**, 168 (2008)

CNT arrays for TIMS



Tong *et al*., IEEE Trans. Comp. & Pack. Tech, **30**, 92 (2007)

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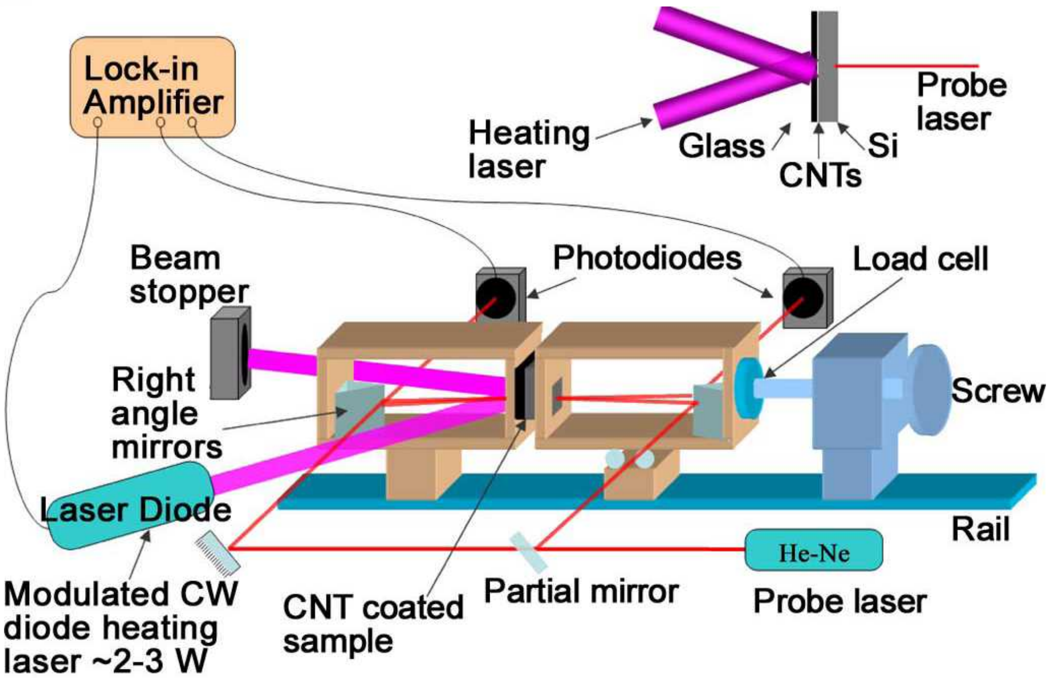
Outline

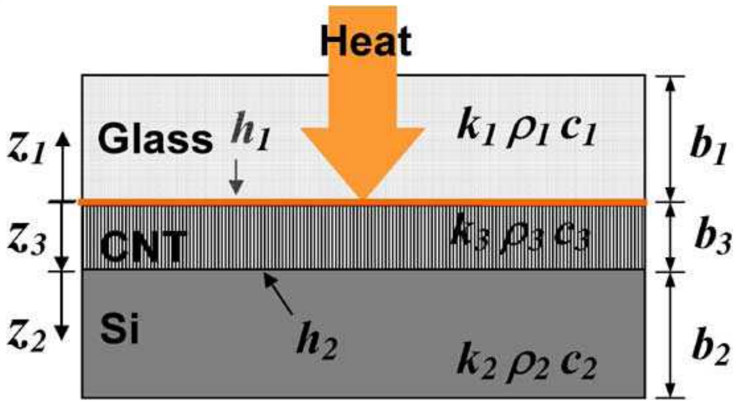
- **Noncontact experimental techniques for measuring Λ and G in nanostructures – PSTR and TTR**

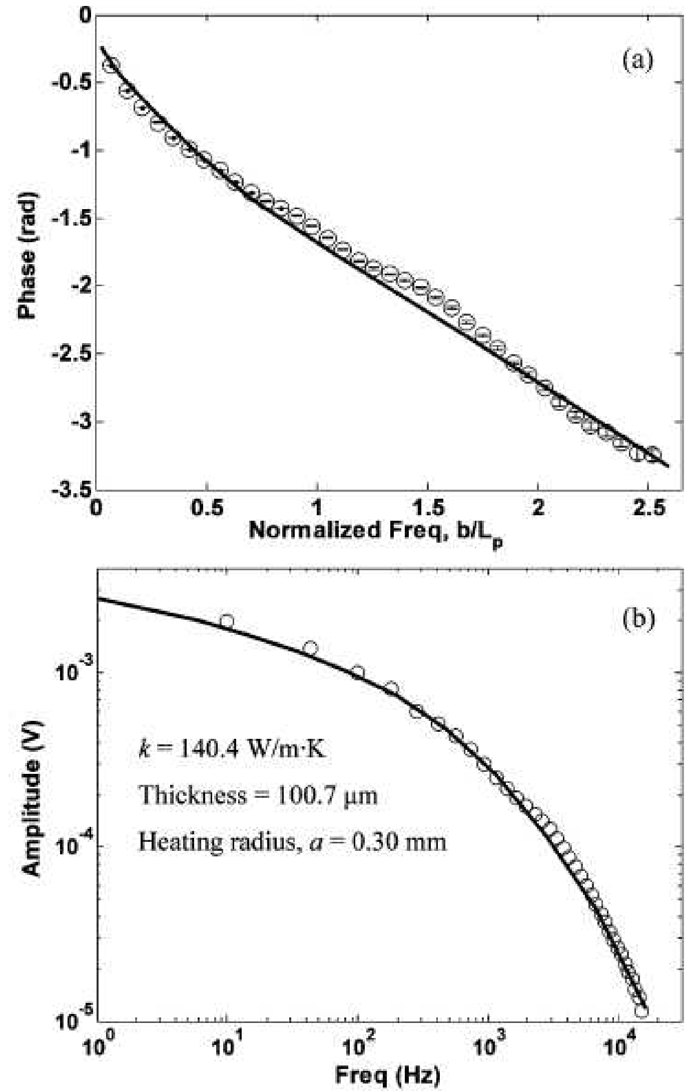
- **Thermal models during laser heating**

- **Sensitivity of PSTR and TTR signals to Λ and G**

PSTR technique

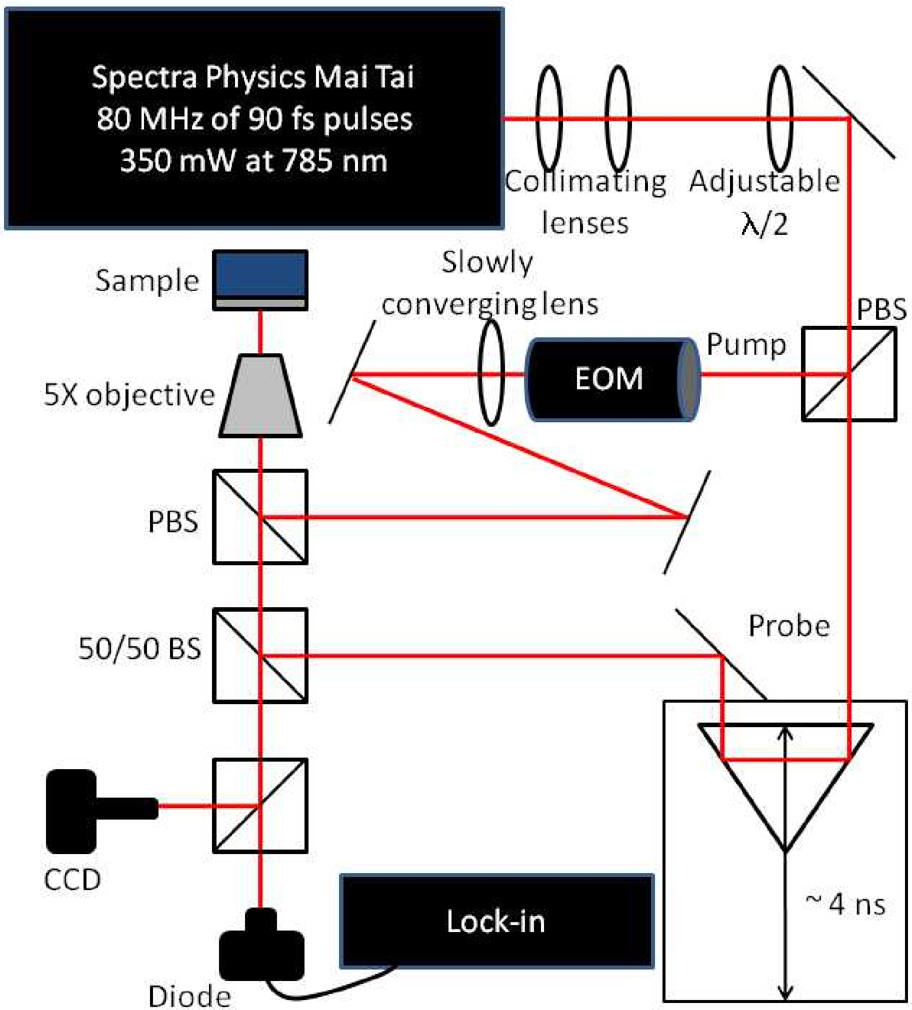


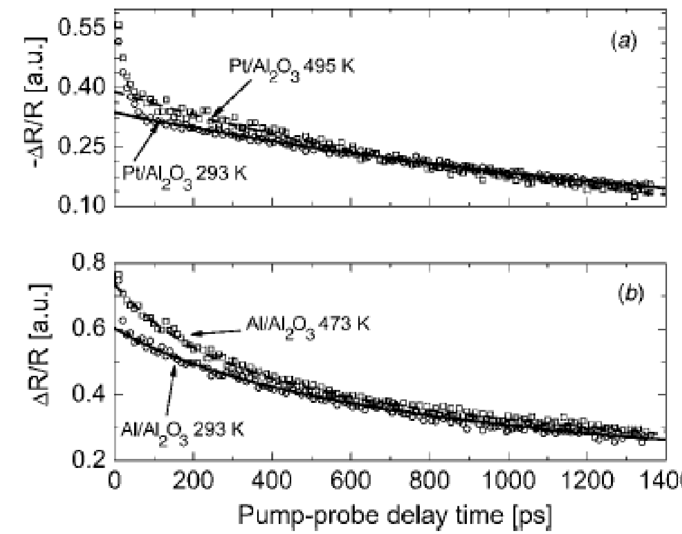


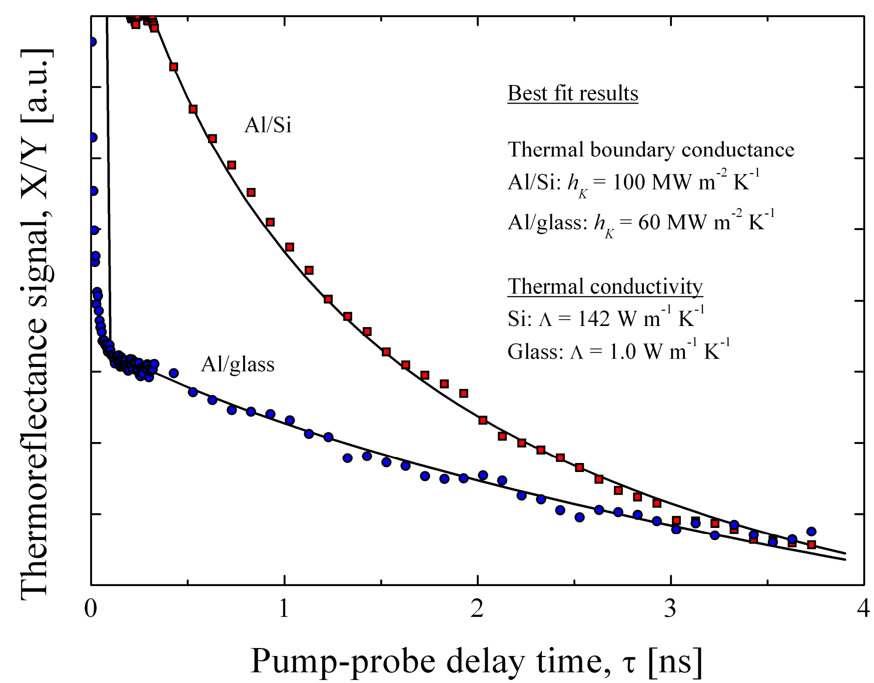


Tong *et al*., IEEE Trans. Comp. & Pack. Tech, **30**, 92 (2007)

TTR technique







Hopkins *et al.*, JHT, **130**, 022401 (2008)

Thermal diffusion due to modulated heat source

Heat equation in cylindrical coordinates due to laser heating

$$C\frac{\partial\theta(z,t)}{\partial t}=\Lambda_z\frac{\partial^2\theta(z,t)}{\partial z^2}+\frac{\Lambda_r}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\theta(z,t)}{\partial r}\right)$$

Transform

$$\frac{\partial^2\theta(\omega)}{\partial z^2}=q^2\theta\ (\omega) \qquad q^2=\frac{\Lambda_r k^2+iC\omega}{\Lambda_z} \qquad q^2=k^2+\frac{iC\omega}{\Lambda_z}$$

Feldman algorithm (Feldman, High Temperatures-High Pressures, **31**, 293 (1999)

$$F(k)=\frac{1}{\gamma_1}\left(\frac{F_{T1}^{+}+F_{T1}^{-}}{F_{T1}^{-}-F_{T1}^{+}}\right) \qquad \begin{bmatrix}F_{T1}^{+}\\ F_{T1}^{-}\end{bmatrix}=\begin{bmatrix}\exp[-q_1d_1] & 0\\ 0 & \exp[q_1d_1]\end{bmatrix}\begin{bmatrix}F_{B1}^{+}\\ F_{B1}^{-}\end{bmatrix}$$

$$\theta(\omega)=\frac{A}{2\pi}\int_0^\infty F(k)\exp\left[\frac{-k^2\left(w_m^2+w_r^2\right)}{8}\right]kdk$$

Need to specify a back side boundary condition

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TTR technique – thermal assumptions

Thermal penetration depth

$$D = \sqrt{\Lambda / (C\pi f)}$$

Thermal penetration time

$$\tau = L^2 C / \Lambda$$

Condition for TTR

$$\tau = 1/(\pi f)$$

Over 8 ns pump-probe delay time (τ), at typical TTR modulation frequencies for film on substrate systems, assume back side of substrate is semi-infinite

$$F(k) = \frac{1}{\gamma_1}\left(\frac{F_{T1}^{+} + F_{T1}^{-}}{F_{T1}^{-} - F_{T1}^{+}}\right)$$

$$\begin{bmatrix} F_{T1}^{+} \\ F_{T1}^{-} \end{bmatrix} = \begin{bmatrix} \exp[-q_1 d_1] & 0 \\ 0 & \exp[q_1 d_1] \end{bmatrix} \begin{bmatrix} F_{B1}^{+} \\ F_{B1}^{-} \end{bmatrix}$$

$$\begin{bmatrix} F_{B1}^{+} \\ F_{B1}^{-} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 + \frac{\gamma_2}{\gamma_1} - \frac{\gamma_2}{G_{12}} & 1 - \frac{\gamma_2}{\gamma_1} + \frac{\gamma_2}{G_{12}} \\ 1 - \frac{\gamma_2}{\gamma_1} - \frac{\gamma_2}{G_{12}} & 1 + \frac{\gamma_2}{\gamma_1} + \frac{\gamma_2}{G_{12}} \end{bmatrix} \begin{bmatrix} F_{T2}^{+} \\ F_{T2}^{-} \end{bmatrix}$$

$$\begin{bmatrix} F_{T2}^{+} \\ F_{T2}^{-} \end{bmatrix} = \begin{bmatrix} 0 \\ \exp[-u_2 d_2] \end{bmatrix}$$

Semi-infinite substrate

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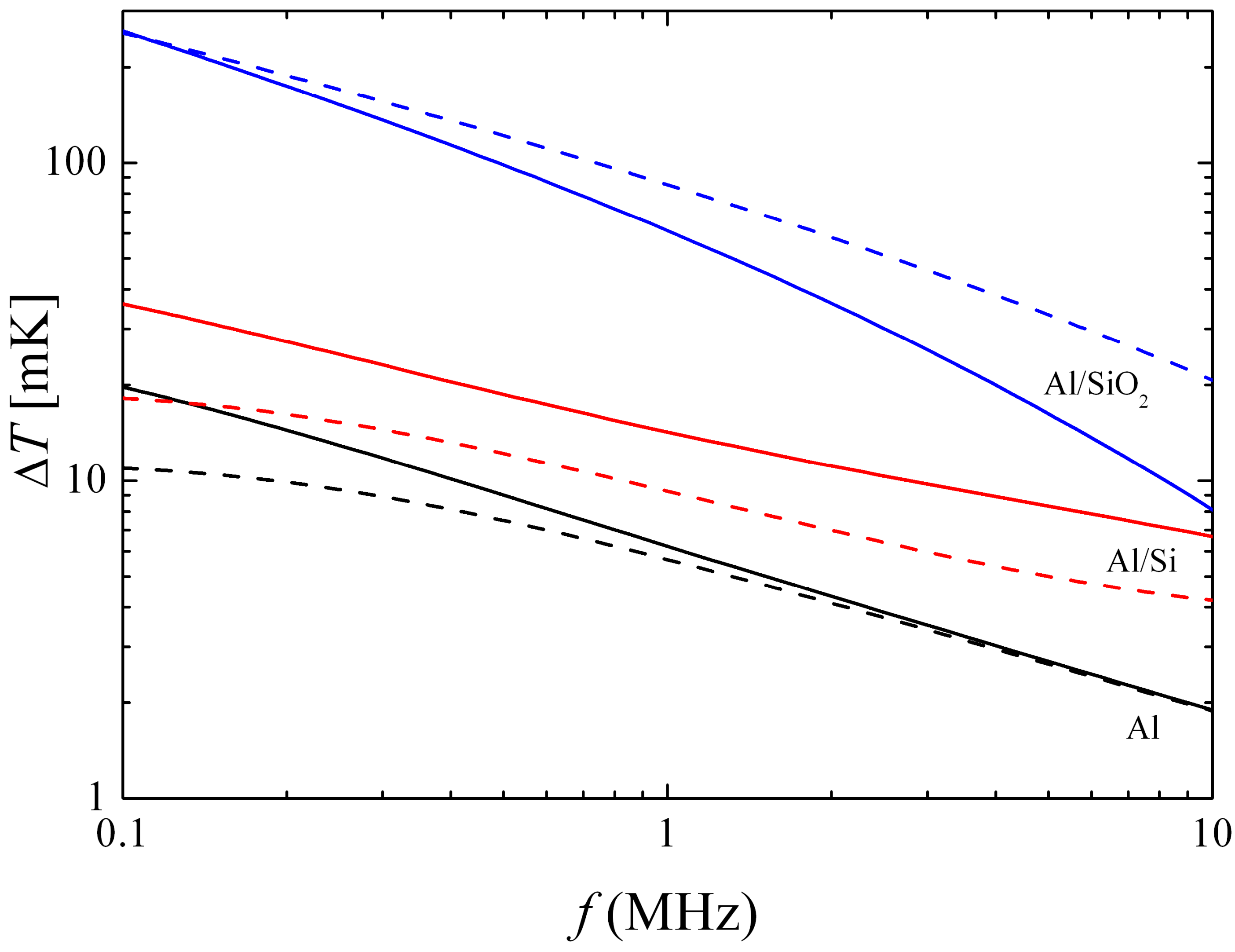
TTR technique – temperature change

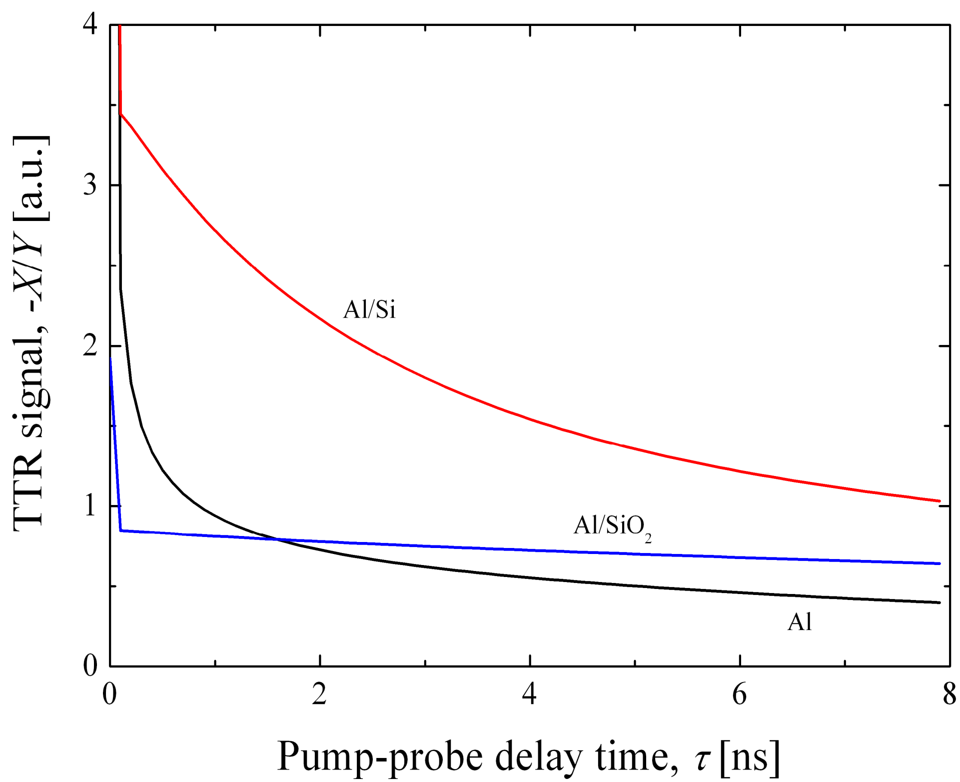


TTR technique – lock in signal

$$R\exp[i(\omega_m t+\phi)]=Z(\omega_m)\exp[i\omega_m t] \qquad Z(\omega_0)=\frac{(2\pi)^2\chi}{\omega_s^2}\sum_{M=-\infty}^{\infty}\theta(\omega_0+M\omega_s)\exp[iM\omega_s\tau]$$

$$X=\mathrm{Re}[Z(\omega_0)],\ Y=\mathrm{Im}[Z(\omega_0)]$$

Cahill, RSI, **75**, 5119 (2004) & Schmidt *et al*., RSI, **79**, 114902 (2008)



PSTR technique – thermal assumptions

Thermal penetration depth

$$D = \sqrt{\Lambda/(C\pi f)}$$

At modulation frequencies typical in PSTR, thermal penetration depth is same order as material system thickness

$$F(k) = \frac{1}{\gamma_1}\left(\frac{F_{T1}^{+} + F_{T1}^{-}}{F_{T1}^{-} - F_{T1}^{+}}\right)$$

$$\begin{bmatrix} F_{T1}^{+} \\ F_{T1}^{-} \end{bmatrix} = \begin{bmatrix} \exp[-q_1 d_1] & 0 \\ 0 & \exp[q_1 d_1] \end{bmatrix} \begin{bmatrix} F_{B1}^{+} \\ F_{B1}^{-} \end{bmatrix}$$

$$\begin{bmatrix} F_{B1}^{+} \\ F_{B1}^{-} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1+\frac{\gamma_2}{\gamma_1}-\frac{\gamma_2}{G_{12}} & 1-\frac{\gamma_2}{\gamma_1}+\frac{\gamma_2}{G_{12}} \\ 1-\frac{\gamma_2}{\gamma_1}-\frac{\gamma_2}{G_{12}} & 1+\frac{\gamma_2}{\gamma_1}+\frac{\gamma_2}{G_{12}} \end{bmatrix} \begin{bmatrix} F_{T2}^{+} \\ F_{T2}^{-} \end{bmatrix}$$

$$\begin{bmatrix} F_{T2}^{+} \\ F_{T2}^{-} \end{bmatrix} = \begin{bmatrix} \exp[-q_1 d_1] & 0 \\ 0 & \exp[q_1 d_1] \end{bmatrix} \begin{bmatrix} F_{B2}^{+} \\ F_{B2}^{-} \end{bmatrix}$$

Assume insulative boundary

$$\begin{bmatrix} F_{B2}^{+} \\ F_{B2}^{-} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} F_{T3}^{+} \\ F_{T3}^{-} \end{bmatrix}$$

$$\begin{bmatrix} F_{T3}^{+} \\ F_{T3}^{-} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

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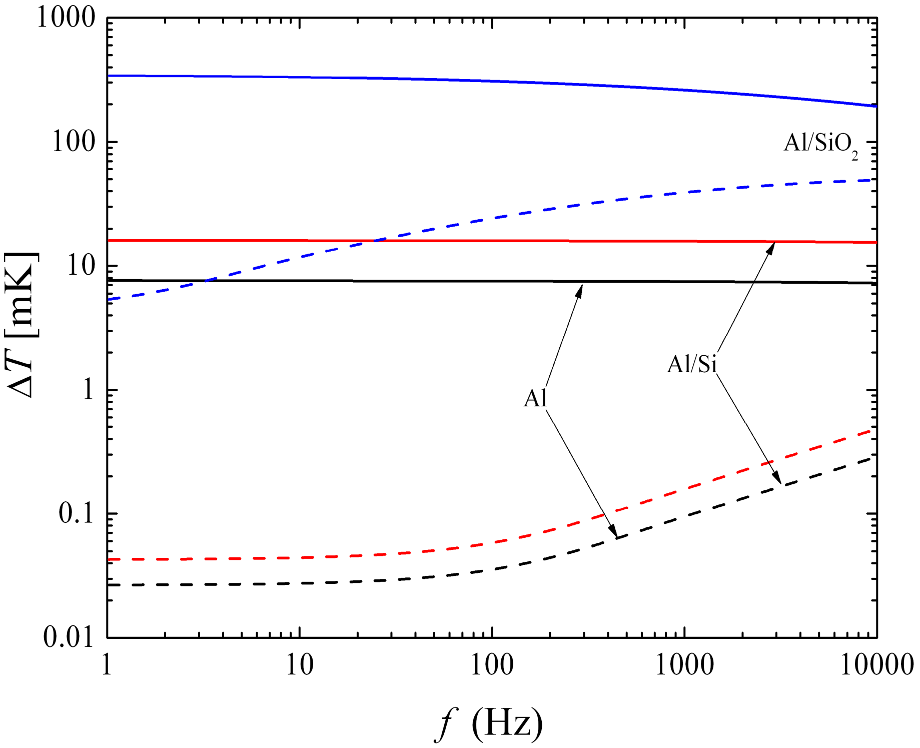
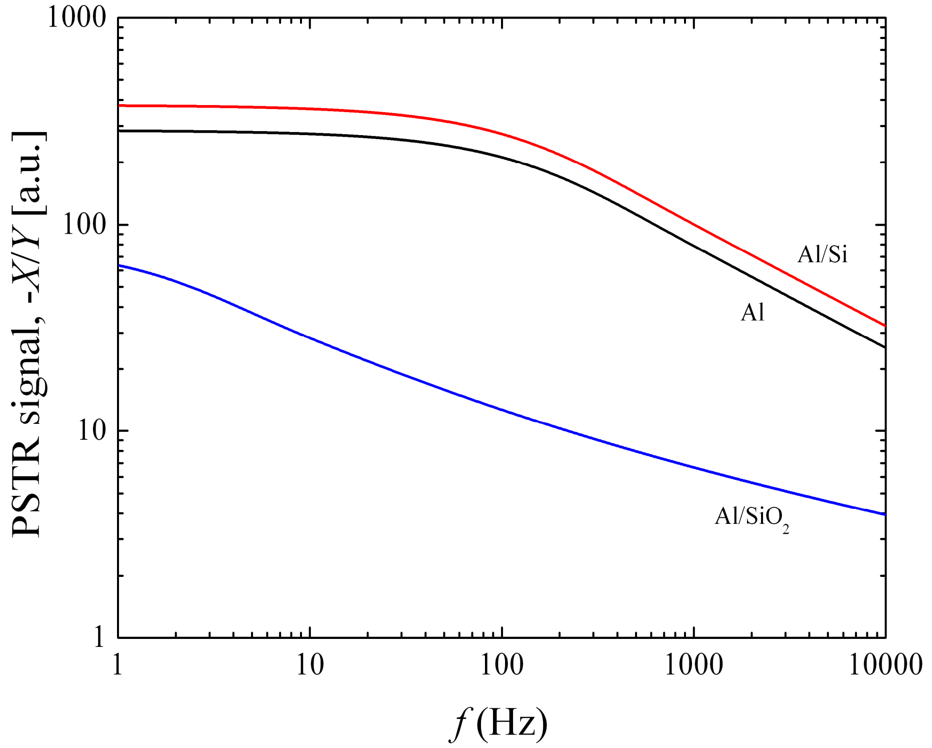
PSTR technique – lock in signal

$$Z(\omega_0) = \chi\theta(\omega_0) \qquad X = \mathrm{Re}[Z(\omega_0)], Y = \mathrm{Im}[Z(\omega_0)]$$

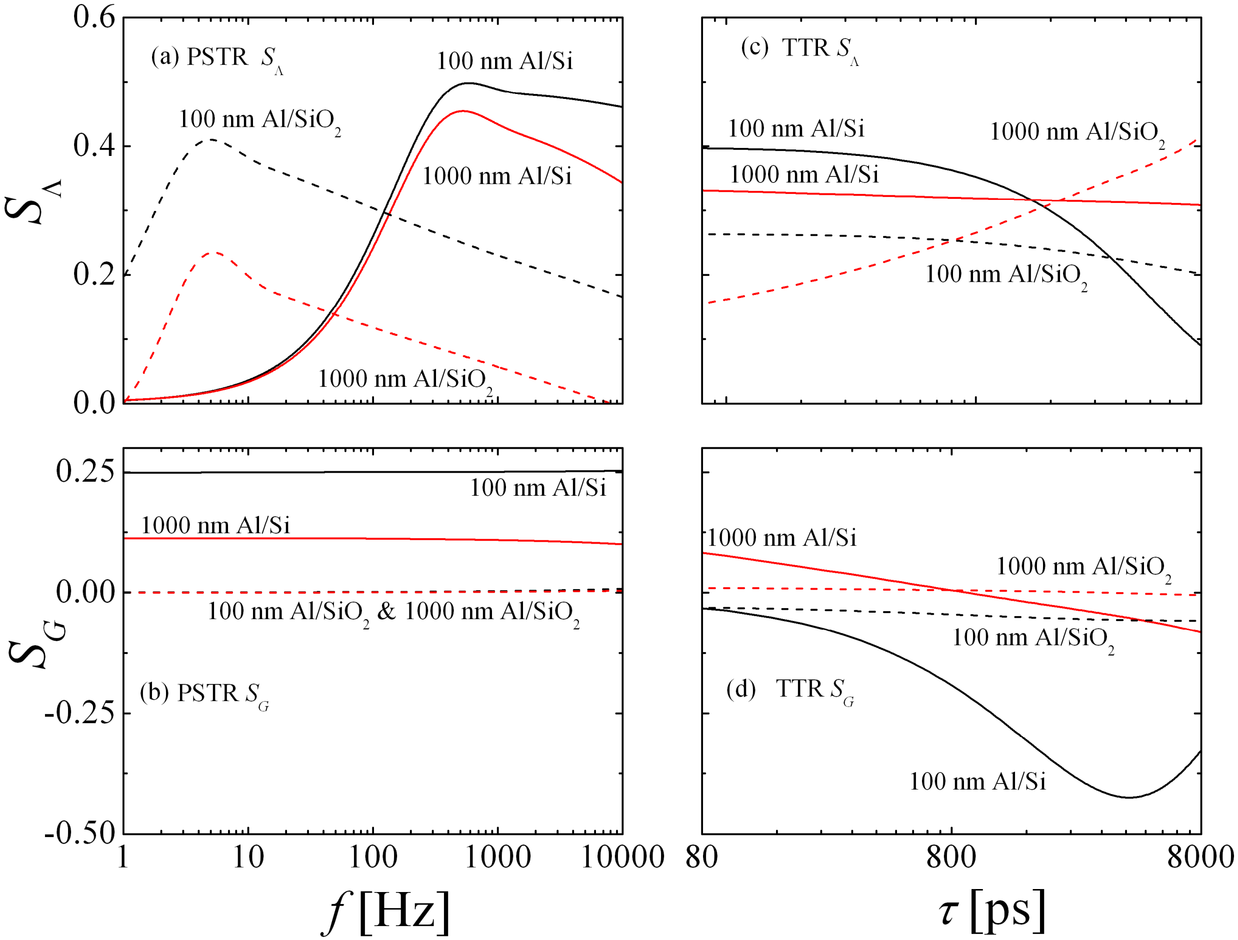




Analysis sensitivities

$$S_\xi = \frac{\partial \ln\left[\frac{-X}{Y}\right]}{\partial \ln[\xi]} = \frac{\xi}{\left(\frac{-X}{Y}\right)} \frac{\partial\left[\frac{-X}{Y}\right]}{\partial[\xi]}$$

Costescu *et al*. PRB, **67**, 054302 (2002)



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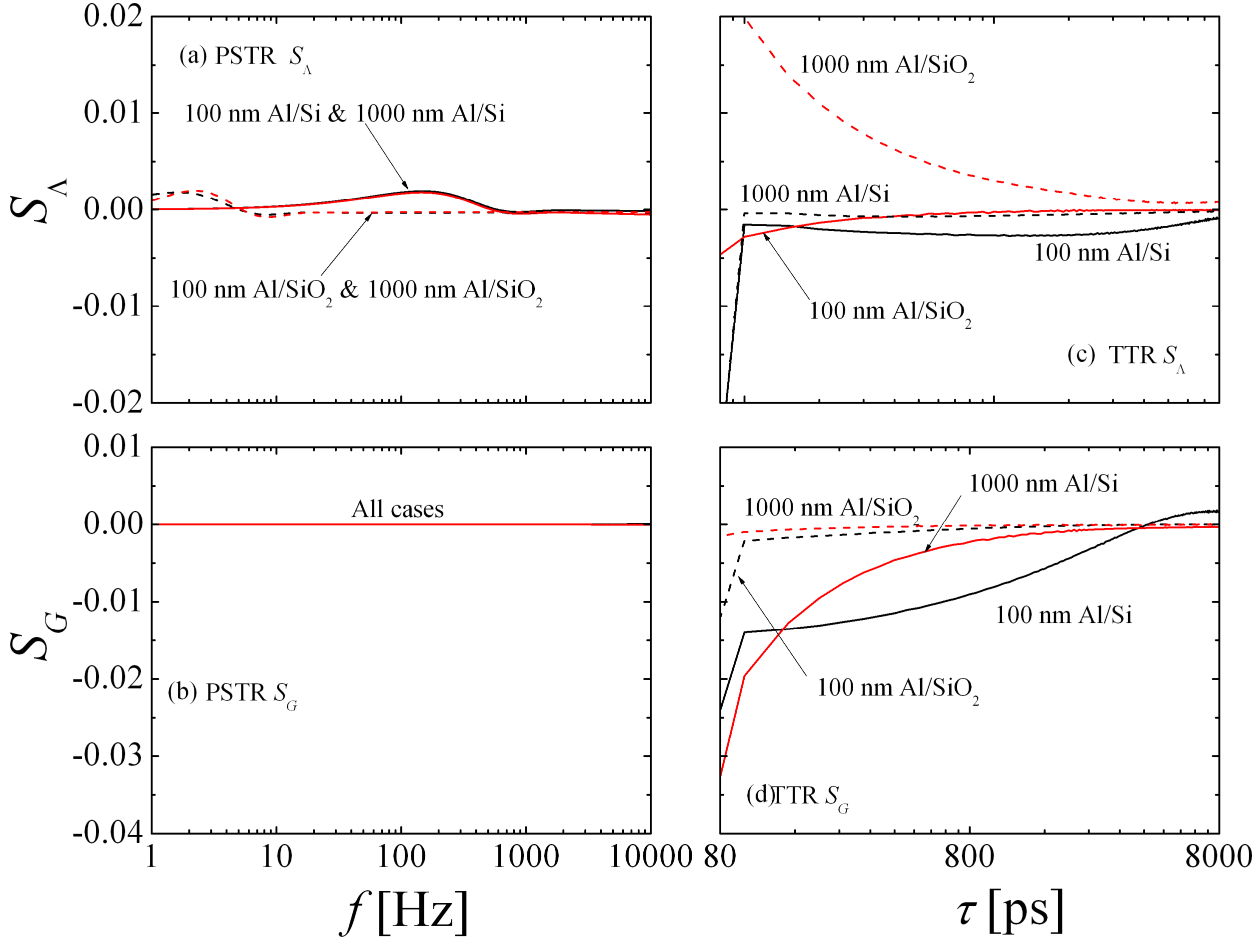
Analysis sensitivities – scaling

$$S_\xi^{PSTR} = \Delta f \frac{\partial}{\partial f}\left[\frac{\xi}{\left(\frac{-X}{Y}\right)}\frac{\partial\left[\frac{-X}{Y}\right]}{\partial[\xi]}\right] \qquad S_\xi^{TTR} = \Delta \tau \frac{\partial}{\partial \tau}\left[\frac{\xi}{\left(\frac{-X}{Y}\right)}\frac{\partial\left[\frac{-X}{Y}\right]}{\partial[\xi]}\right]$$



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Conclusions

- Feldman algorithm for semi-infinite and insulative substrate system leads to lock-in response - -X/Y
- TTR and PSTR techniques both sensitive to G and Λ if all experimental parameters are known (spot sizes, absorbed power, electronic gain, etc.)
- If parameters are unknown and model must be scaled to data, TTR is far superior except for measuring conductivity of bulk, conductive systems

Acknowledgements

- LDRD program office through the Sandia National Laboratories Harry S. Truman Fellowship.
- Allen Gorby, Sean Kearney, Tom Grasser, Tom Harris, Thomas Beechem, Ed Barnat

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