Percolation noise at the metal–insulator transition of nanostructured VO_2 films

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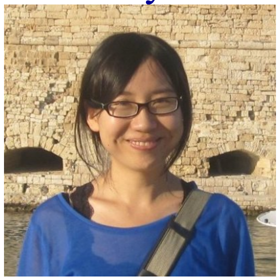
Measurements: (2008 unsuccessful) successful: 2012 – 2014

Zareh Laszlo

Shuyi



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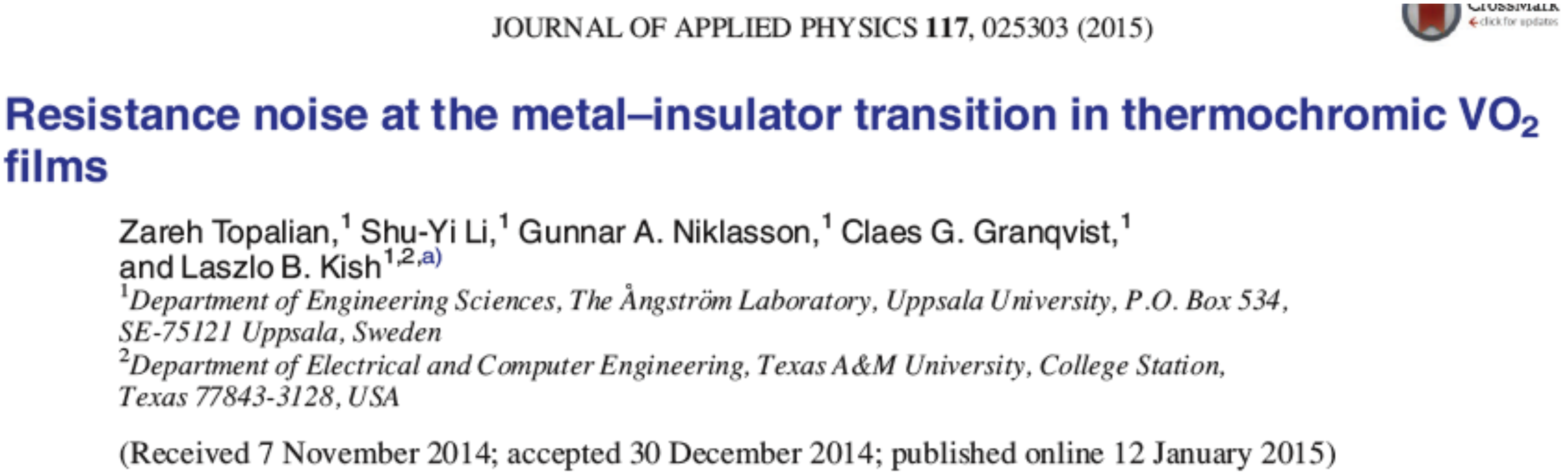

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Resistance noise at the metal–insulator transition in thermochromic VO_2 films

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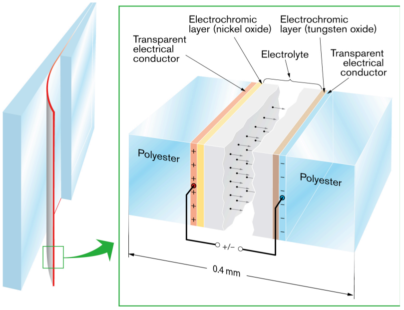
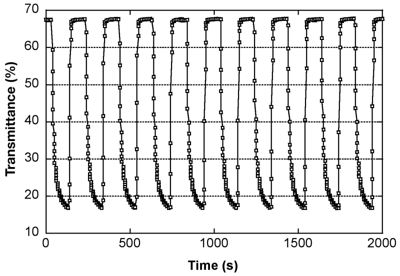
Thermochromic VO_2 films were prepared by reactive DC magnetron sputtering onto heated sapphire substrates and were used to make 100-nm-thick samples that were 10 μm wide and 100 μm long. The resistance of these samples changed by a factor ~2000 in the $50 < T_s < 70$ ºC range of temperature T_s around the “critical” temperature T_c between a low-temperature semiconducting phase and a high-temperature metallic-like phase of VO_2. Power density spectra $S(f)$ were extracted for resistance noise around T_c and demonstrated unambiguous $1/f$ behavior. Data on $S(10\text{ Hz})/R_s^2$ scaled as R_s^x, where R_s is sample resistance; the noise exponent x was –2.6 for $T_s < T_c$ and +2.6 for $T_s > T_c$. These exponents can be reconciled with the Pennetta–Trefán–Reggiani theory [C. Pennetta, G. Trefán, and L. Reggiani, Phys. Rev. Lett. 85, 5238 (2000)] for lattice percolation with switching disorder ensuing from random defect generation and healing in steady state. Our work hence highlights the dynamic features of the percolating semiconducting and metallic-like regions around T_c in thermochromic VO_2 films.

VO_2: applications thermochromic glazing

Energy-Saving Applications. Smart-windows:
Voltage or temperature controlled transparency





Transparent **Darkened**

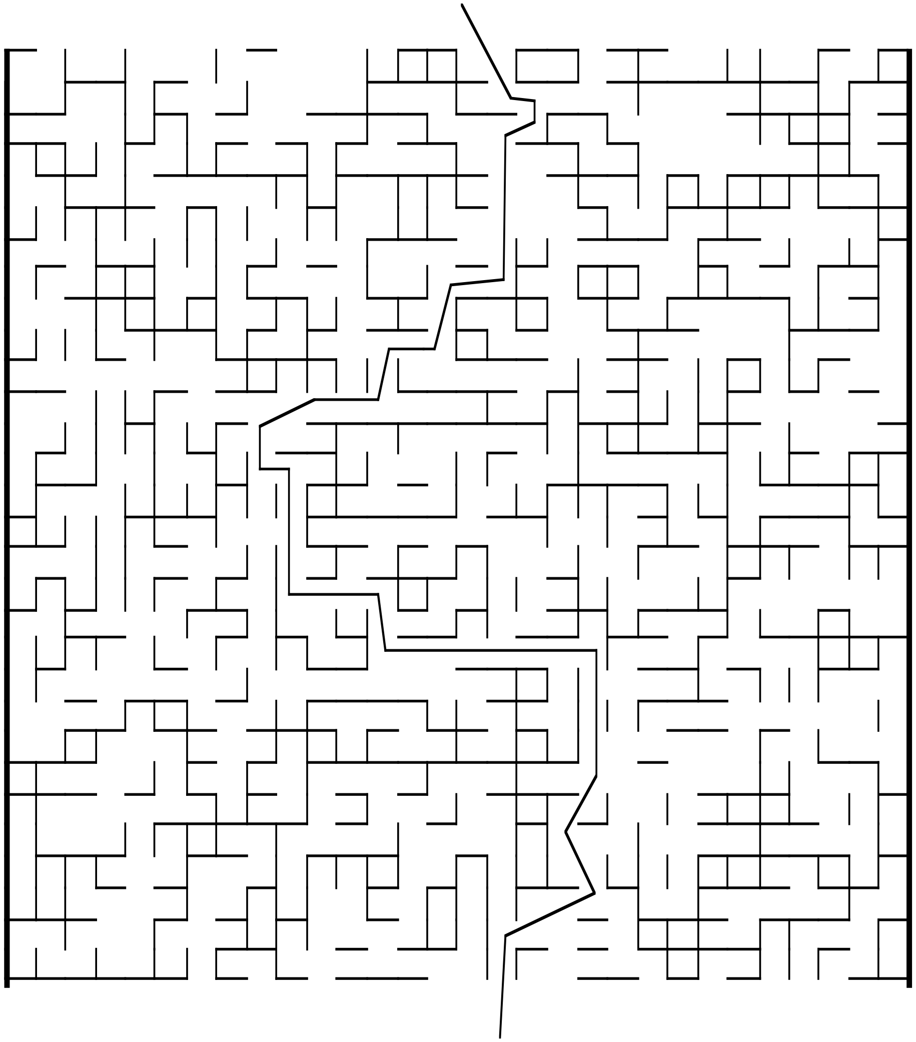
VO_2:

- Thermochromic [F. J. Morin, Phys. Rev. Lett. 3, 34 (1959)];

- Single crystal: first-order metal–insulator transition (MIT) at Tc ≈ 68 ºC; switching between a low-temperature (monoclinic) *semiconducting* state and a high-temperature (rutile) *metallic*-like state.

- Thin films: the MIT is gradual with *metallic*-like regions growing in extent as the sample temperature T_s approaches T_c from below and with *semiconducting* regions disappearing as T_s becomes increasingly larger than T_c.

Lattice percolation



$$R(p) \propto \left(p - p_c\right)^{-t}$$

p: filling factor (0 – 1)
p_c: percolation threshold

t: resistivity exponent (1 - 2)
depends on dimension only (in regular lattices)

because percolation length is scaling in a similar fashion

$$\frac{S_R(f)}{R^2} \propto R^x$$

resistivity and noise exponent depends on dimension only (in regular lattices) and their absolute value is the same in 2D for conductor-insulator/superconductor transition (due to duality in 2D)

figure from: Z. Gingl, et al, Semicond. Sci. & Technol. 11 (1996) 1770.

Lattice percolation is confirmed in VO_2 films by J. Rozen, et al, Appl. Phys. Lett. 88, 081902 (2006).

p: determined from transparance measurements

$$R(p) \propto (p - p_c)^{-t}$$

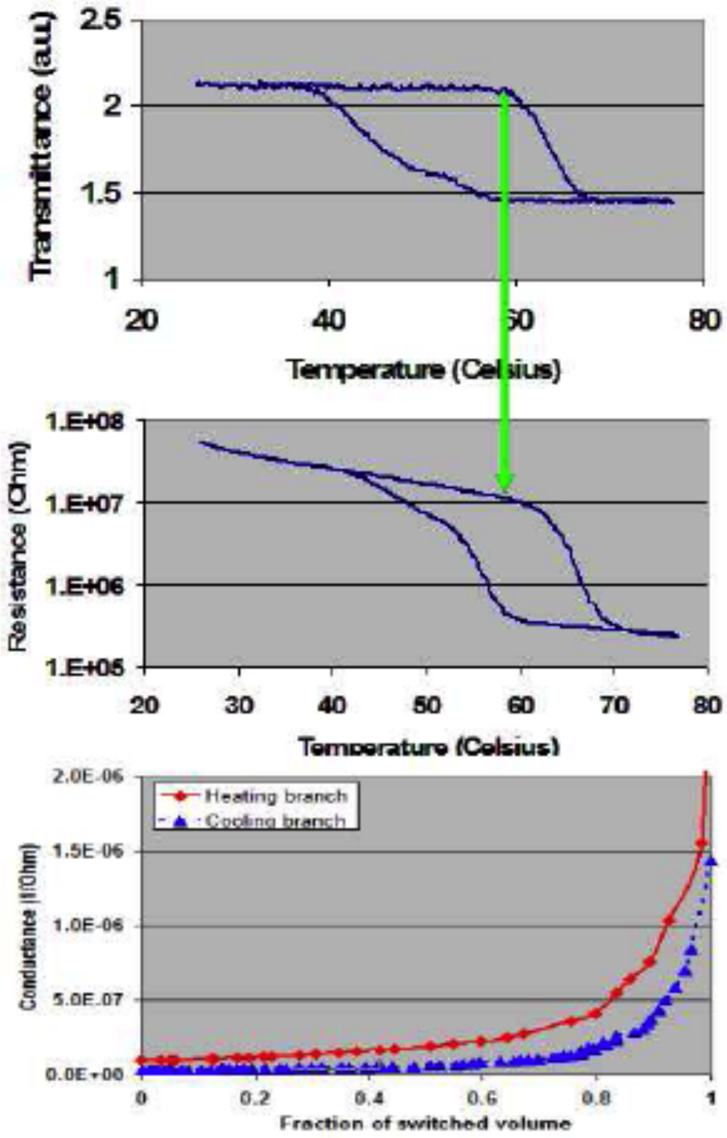
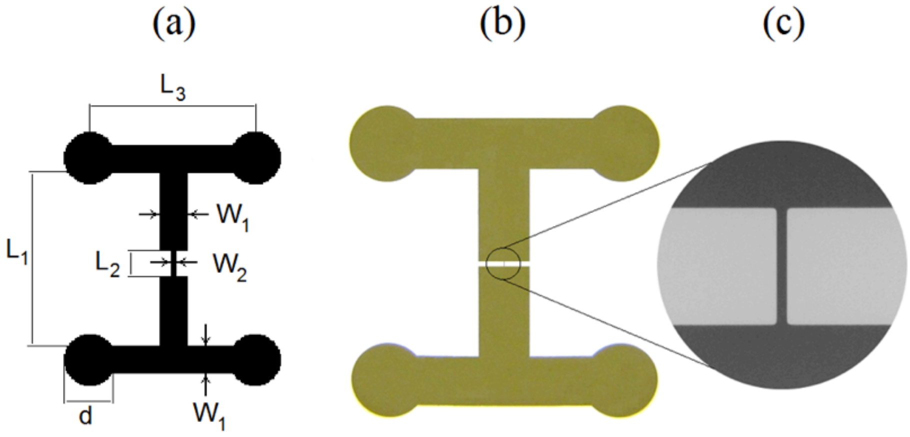


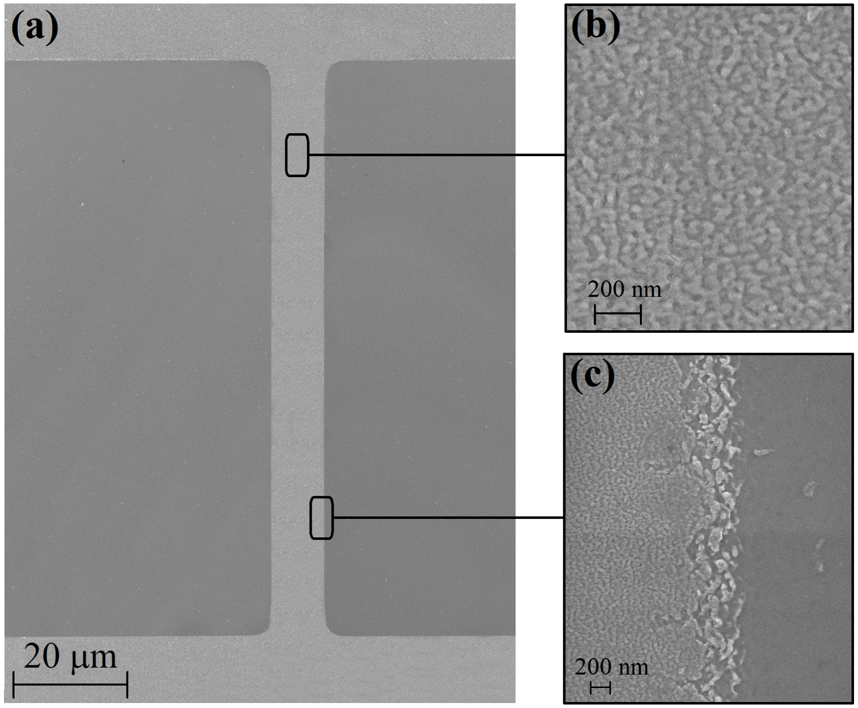
FIG. 3 Transmittance (a) and resistance (b) curves measured simultaneously as a function of temperature. (c) Dependance of the conductance on the volume fraction of the metallic phase deduced from the experimental data.

Noise experiments.

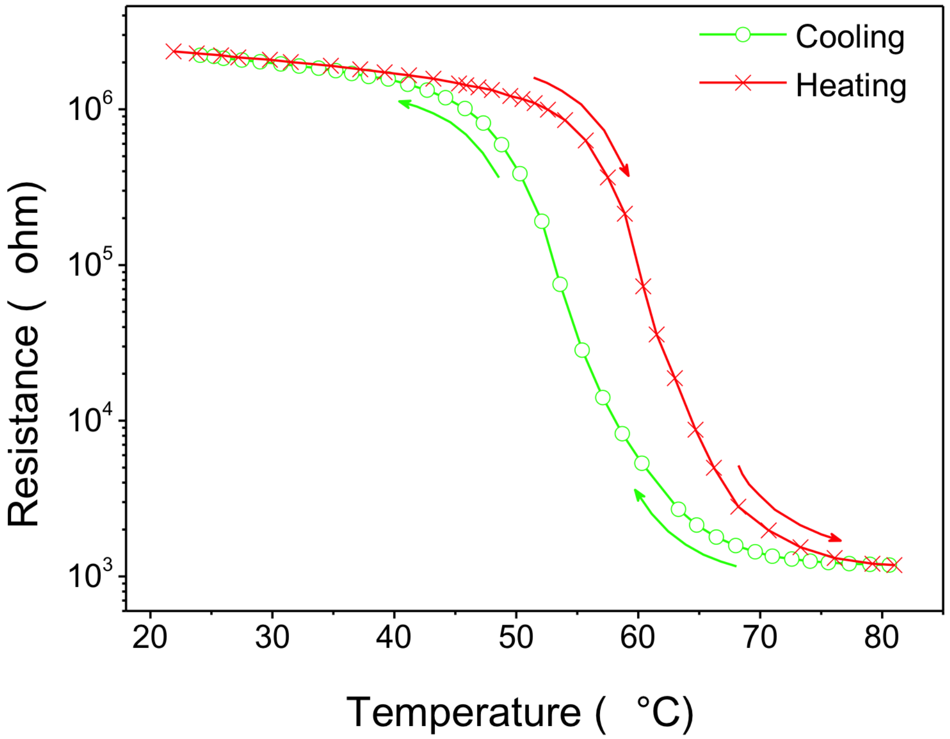
Schematic illustration of a **100-nm**-thick VO_2 sample with a micro-bridge in the middle and with contact pads for four-point electrical measurements. The dimensions are L_1 = 5 mm, L_2 = **100 µm**, L_3 = 6 mm, d = 1.5 mm, W_1 = 1 mm and W_2 = **10 µm**. Panels (b) and (c) are photos of the same structure and of the VO2 micro-bridge in the encircled region, respectively.



SEM micrographs of the VO2 micro-bridge



Resistance measurements



Extraordinary temperature sensitivity. For successful conductance noise measurements, it requires *ultra-low noise temperature control*, which is not available on the market.

We had similar problems in the 1990's with measuring high-T_c superconductor noise.

VOLUME 71, NUMBER 17 PHYSICAL REVIEW LETTERS 25 OCTOBER 1993

New Noise Exponents in Random Conductor-Superconductor and Conductor-Insulator Mixtures

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(Received 29 April 1993)

Time dependent fluctuations of the fraction of normal-conducting part in random resistor-superconductor (RS) and resistor-insulator (RI) networks lead to a novel effect close to the percolation threshold. The normalized noise scales as a function of the resistance with a characteristic exponent λ. The value of λ is different from the value found in classical percolation models but can be related to the resistivity exponent s (t) of the RS (RI) transition by a simple scaling relation: $\lambda = 2/s$ ($2/t$). Results of recent experiments on high-T_c superconducting thin films are interpreted in terms of this new effect and a crossover from three to two dimensional percolation behavior is found.

September 19, 1989

Peter

Laszlo

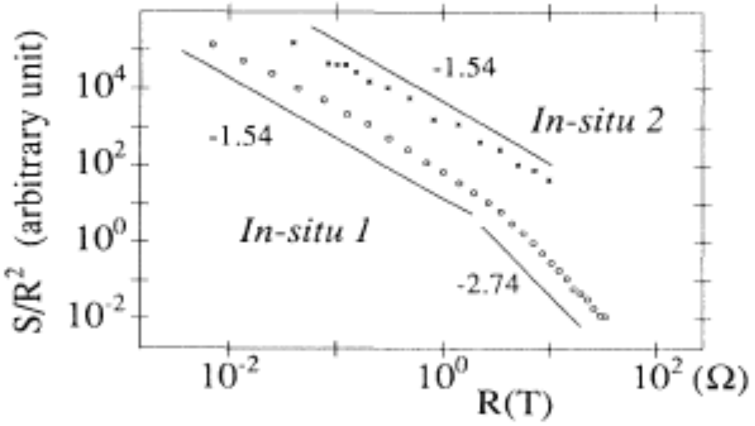


FIG. 1. Normalized noise versus resistance in high-quality high-T_c superconducting thin films in the percolation region. *In situ 1*: sample fabricated by coevaporation. *In situ 2*: sample fabricated by dc magnetron sputtering. The solid lines correspond to slopes predicted by scaling theory.

Ultra-low noise temperature control (originally developed by Per Nordblad, which we modified for the new needs)

- **P. Nordblad**, "Magnetic Anisotropy and Magnetic Phase Transitions of Iron and Manganese Compounds", in Abstracts of Uppsala Dissertations from the Faculty of Science 556, Acta Universitatis Upsaliensis (Uppsala, Sweden, 1980).

- P. Svedlindh, K. Gunnarsson, P. Nordblad, L. Lundgren, H. Aruga, and A. Ito, Phys. Rev. B 40, 7162 (1989).

- ***Copper thermometer*, (DC-) *heater* and the film sample on *the same copper block*;**

- **in vacuum, thus *passive thermal relaxation time* > 1000 seconds;**

- **thermometer with 4-point driving/probing arrangement with a differential transformer;**

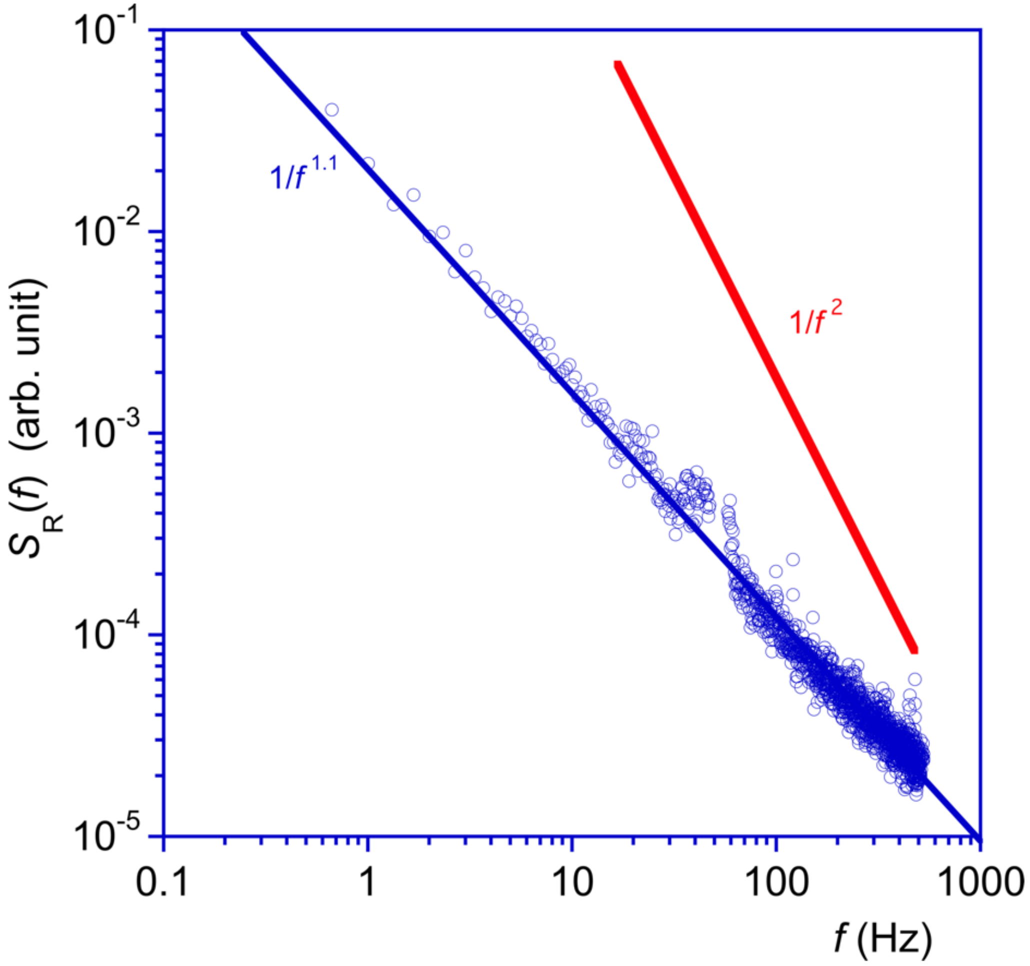
- **temperature measurement bridge is of high-stability resistors in oil bath**

- **which is driven by AC, 473Hz to reduce 50 Hz harmonics, generated, filtered/measured by a *lockin amplifie*r**

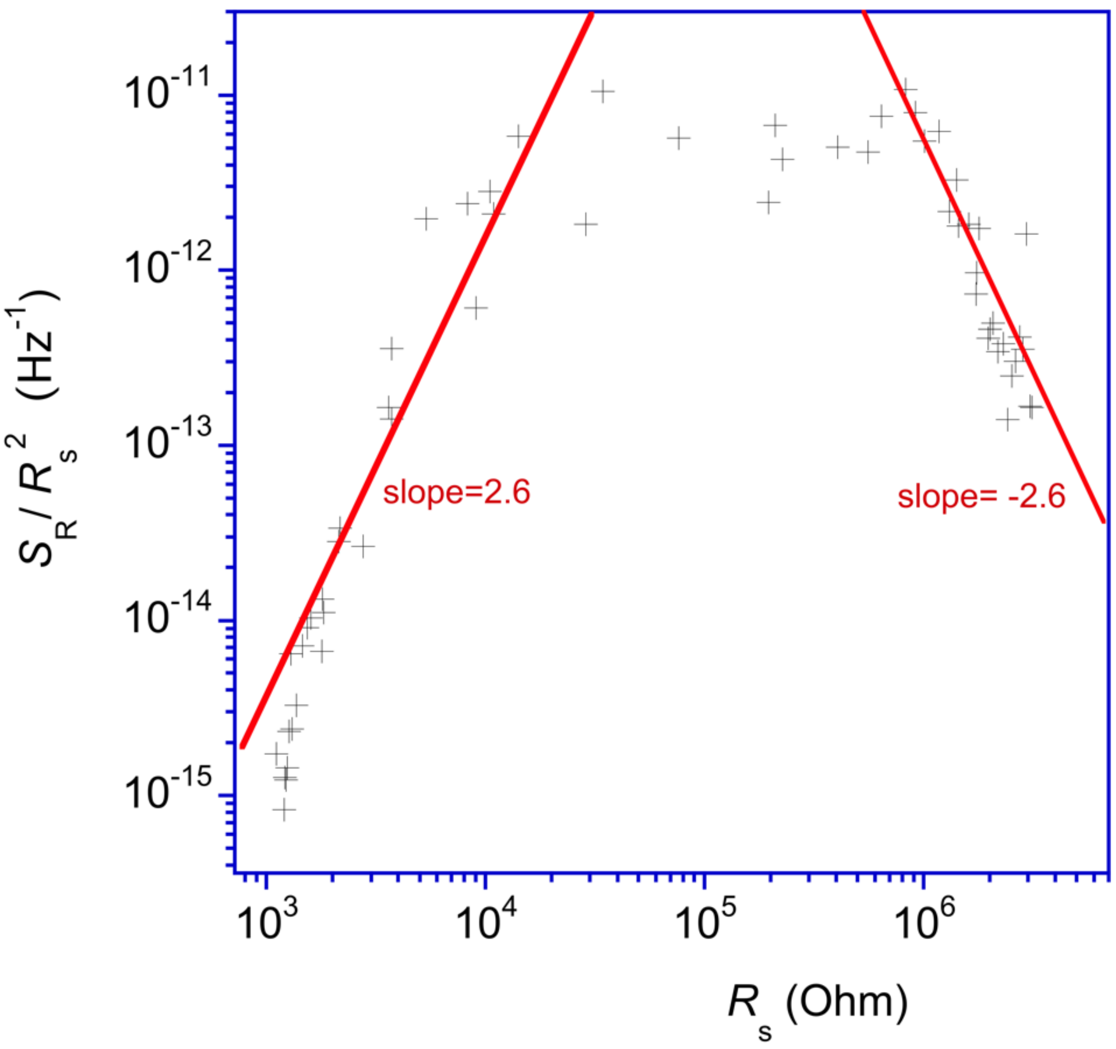
- **lockin DC output is driving a PID controller, which drives the analog DC heater amplifier.**

Temperature noise less than 10^{-9} K/Hz$^{0.5}$ can be achieved.

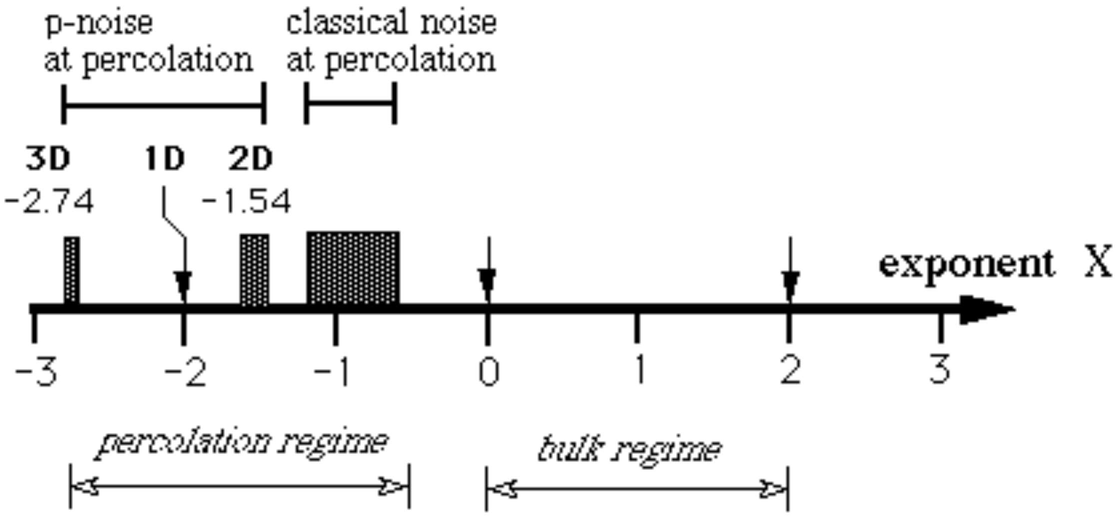
Conductance noise spectrum and checking for temperature fluctuations ($1/f^2$)

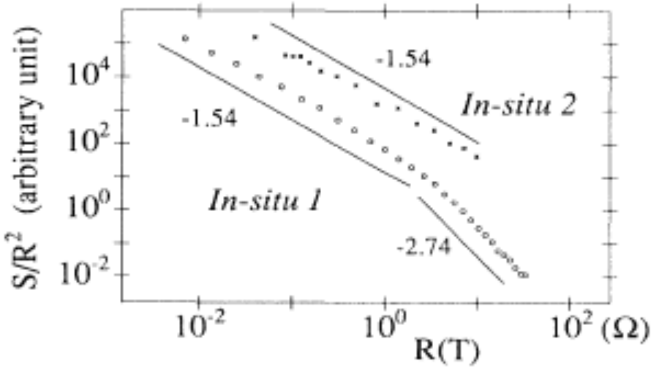


Scaling plot of the normalized noise versus the resistance



Our measured/fitted noise exponents in various high-Tc superconductor films (1989-1994)





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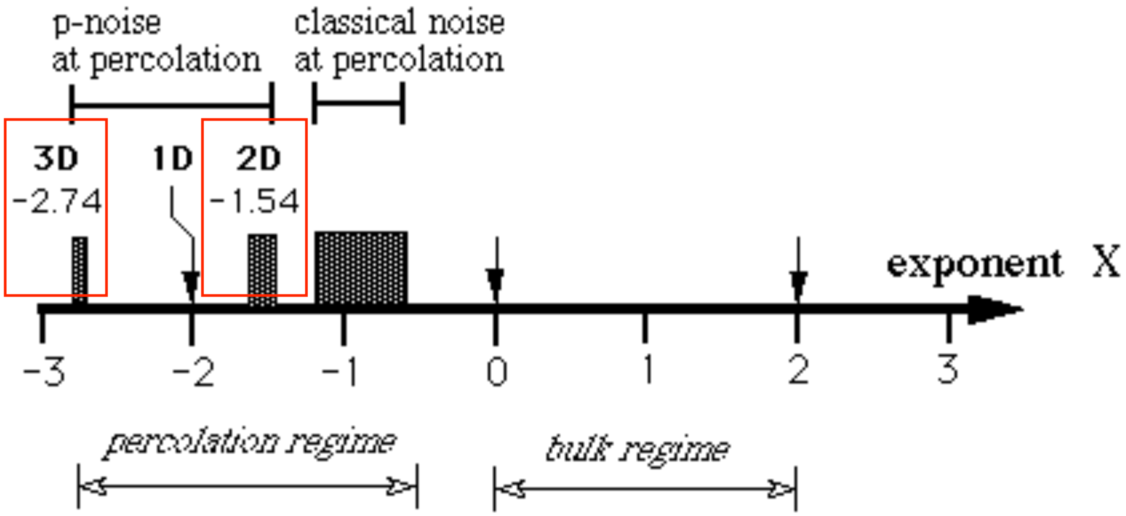
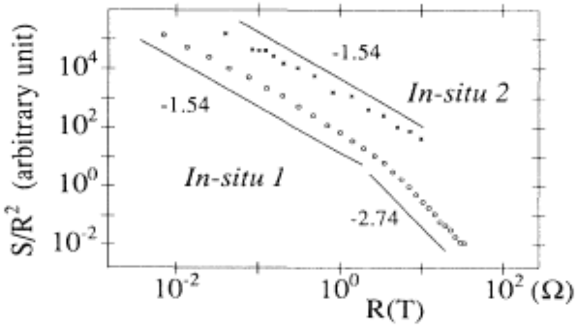


The -2.7 exponent would be fine at the high-temperature end however that is the 3D case where duality [P.M. Hui and D. Stroud, Phys. Rev. B 34, 8101 (1986)] does not force the same absolute value in at the low-temperature end as at the high one.



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Kiss-Svedlindh, PRL 1993.

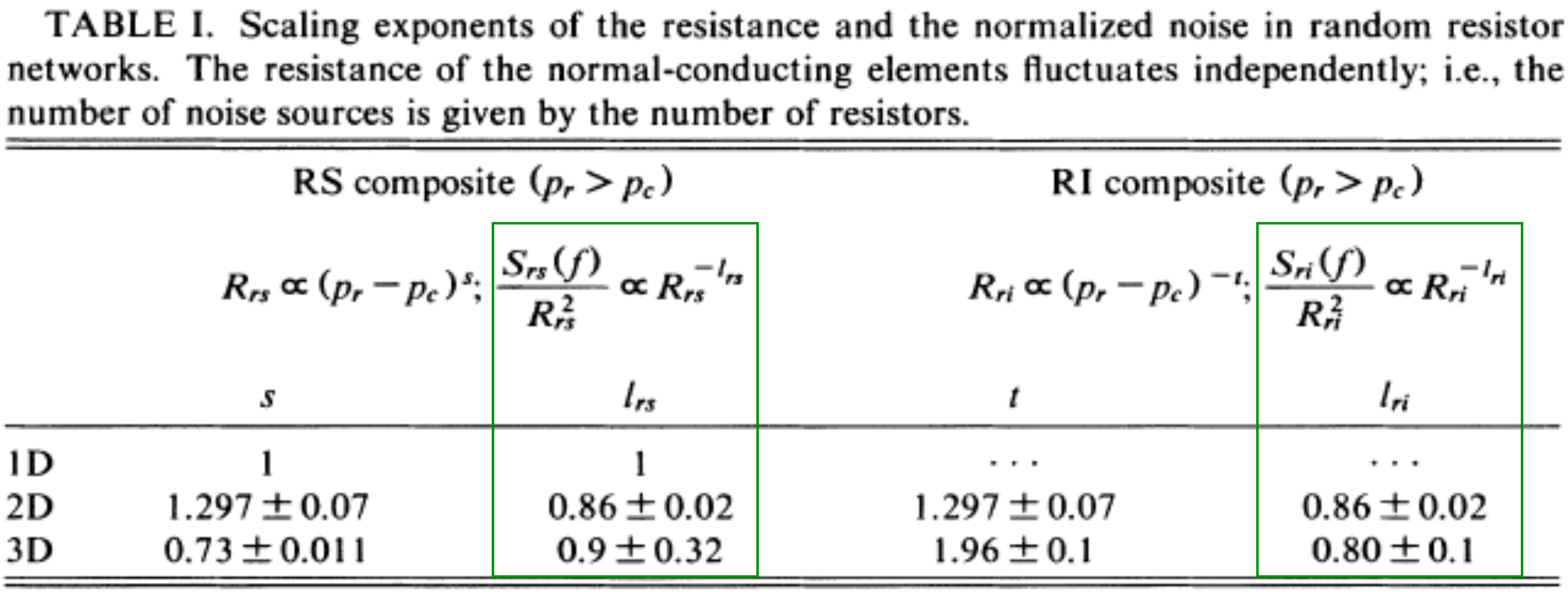


TABLE I. Scaling exponents of the resistance and the normalized noise in random resistor networks. The resistance of the normal-conducting elements fluctuates independently; i.e., the number of noise sources is given by the number of resistors.

	RS composite ($p_r > p_c$)		RI composite ($p_r > p_c$)	
	$R_{rs} \propto (p_r - p_c)^s$;	$\frac{S_{rs}(f)}{R_{rs}^2} \propto R_{rs}^{-l_{rs}}$	$R_{ri} \propto (p_r - p_c)^{-t}$;	$\frac{S_{ri}(f)}{R_{ri}^2} \propto R_{ri}^{-l_{ri}}$
	s	l_{rs}	t	l_{ri}
1D	1	1	...	...
2D	1.297 ± 0.07	0.86 ± 0.02	1.297 ± 0.07	0.86 ± 0.02
3D	0.73 ± 0.011	0.9 ± 0.32	1.96 ± 0.1	0.80 ± 0.1

Kiss-Svedlindh, p-fluctuations, percolation noise model, 1993

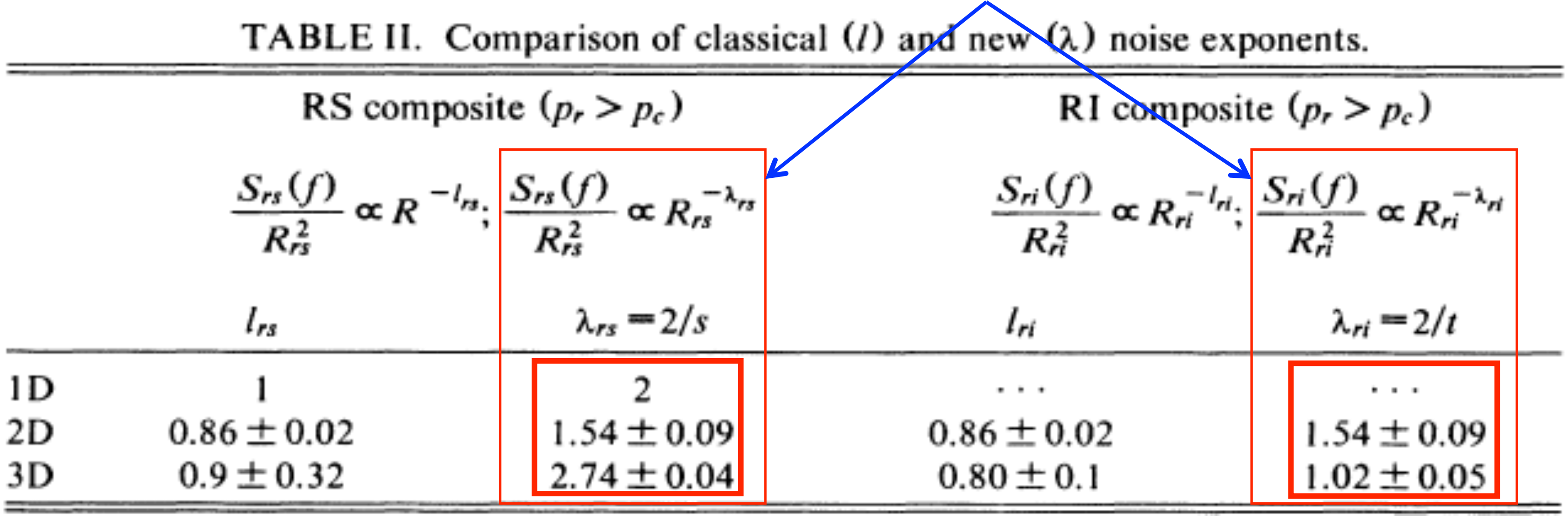
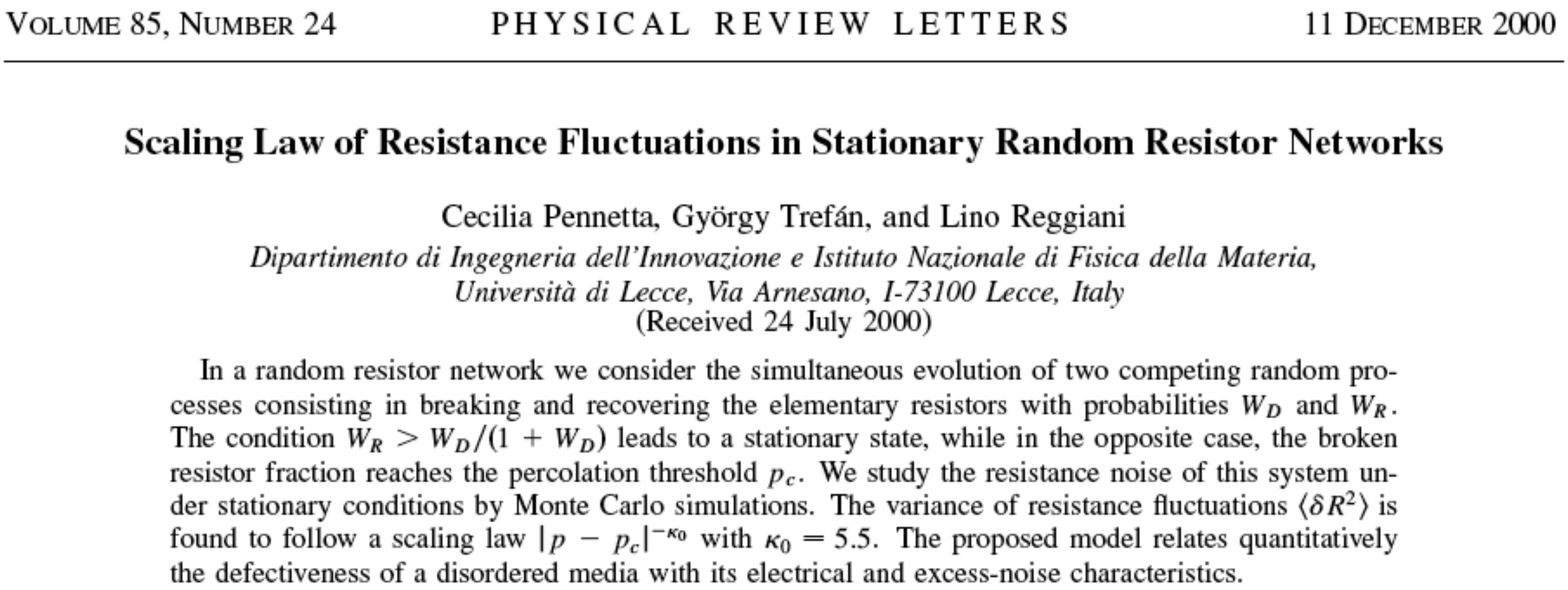


TABLE II. Comparison of classical (l) and new (λ) noise exponents.

	RS composite ($p_r > p_c$)		RI composite ($p_r > p_c$)	
	$\frac{S_{rs}(f)}{R_{rs}^2} \propto R^{-l_{rs}}$;	$\frac{S_{rs}(f)}{R_{rs}^2} \propto R_{rs}^{-\lambda_{rs}}$	$\frac{S_{ri}(f)}{R_{ri}^2} \propto R_{ri}^{-l_{ri}}$;	$\frac{S_{ri}(f)}{R_{ri}^2} \propto R_{ri}^{-\lambda_{ri}}$
	l_{rs}	$\lambda_{rs} = 2/s$	l_{ri}	$\lambda_{ri} = 2/t$
1D	1	2	...	...
2D	0.86 ± 0.02	1.54 ± 0.09	0.86 ± 0.02	1.54 ± 0.09
3D	0.9 ± 0.32	2.74 ± 0.04	0.80 ± 0.1	1.02 ± 0.05



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Scaling Law of Resistance Fluctuations in Stationary Random Resistor Networks

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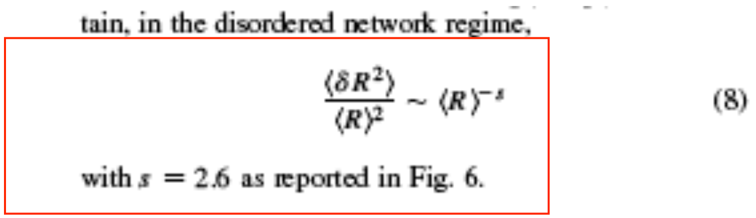
Università di Lecce, Via Arnesano, I-73100 Lecce, Italy

(Received 24 July 2000)

In a random resistor network we consider the simultaneous evolution of two competing random processes consisting in breaking and recovering the elementary resistors with probabilities W_D and W_R. The condition $W_R > W_D/(1 + W_D)$ leads to a stationary state, while in the opposite case, the broken resistor fraction reaches the percolation threshold p_c. We study the resistance noise of this system under stationary conditions by Monte Carlo simulations. The variance of resistance fluctuations $\langle \delta R^2 \rangle$ is found to follow a scaling law $|p - p_c|^{-\kappa_0}$ with $\kappa_0 = 5.5$. The proposed model relates quantitatively the defectiveness of a disordered media with its electrical and excess-noise characteristics.

The **Pennetta-Trefan-Reggiani** model of "dynamical percolation" with microscopic damage and healing processes with separate rates in 2D produces 2.6 exponents in the steady-state at low-temperature.

In 2D, *due to duality* [P. M. Hui and D. Stroud, Phys. Rev. B 34, 8101 (1986)], the same absolute exponent value holds in the high-temperature limit with negative sign.



tain, in the disordered network regime,

$$\frac{\langle \delta R^2 \rangle}{\langle R \rangle^2} \sim \langle R \rangle^{-s} \qquad (8)$$

with $s = 2.6$ as reported in Fig. 6.

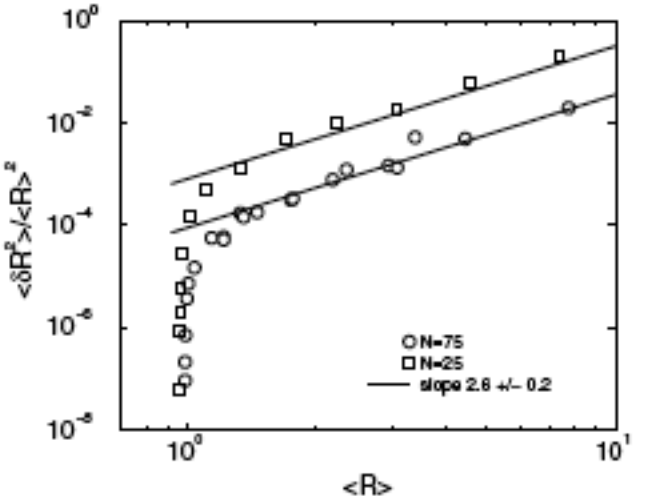
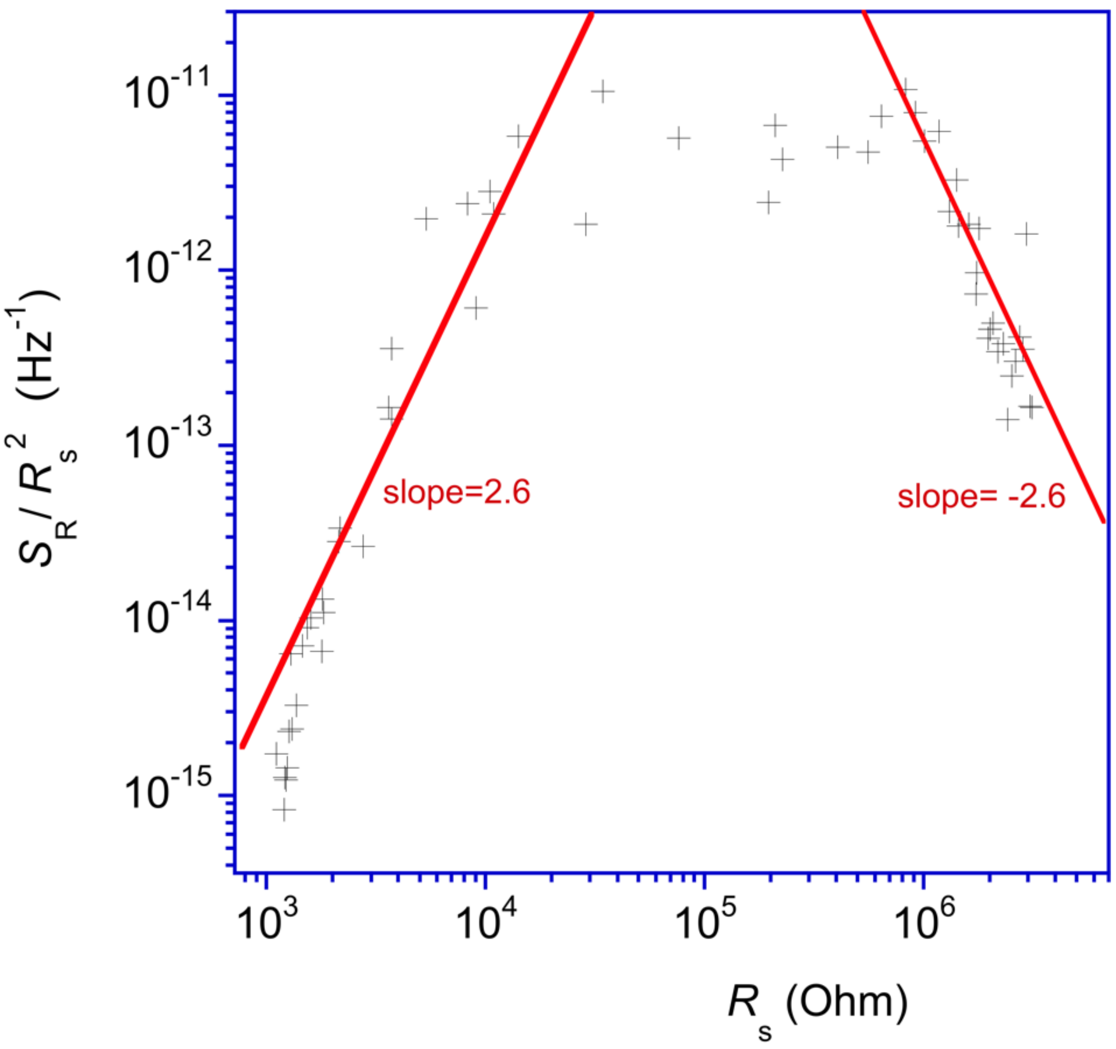


FIG. 6. Resistance noise normalized to the square of the average RRN resistance $\langle \delta R^2 \rangle / \langle R \rangle^2$ as a function of the average resistance $\langle R \rangle$.

in the percolation (scaling) region:

$$\boxed{\frac{S_R(f)}{R^2} \propto R^x \quad \text{with} \quad x \approx \pm\ 2.6}$$

Scaling plot of the normalized noise versus the resistance



UPoN!!!

- In the PTR model, the noise is not inherent in the resistance but comes from the switching

- PTR see Lorentzian spectra. How do we get 1/f noise?

- Hierarchy of switching time constants?

- Why is the spectrum 1/f in the whole temperature range?

- Perhaps another model is relevant?