1/f fluctuations in organic semiconductors: a percolative model

Does current noise arise from the competition between conductive and insulating phase at the trap-filling transition?

Anna Carbone, Bogumila Kotowska, Dariusz Kotowski

- Physics Department, Politecnico di Torino, Italy
- ISMAC- CNR Inst. for the Study of Macromolecules, Milan, Italy
- Gdansk University of Technology, Poland

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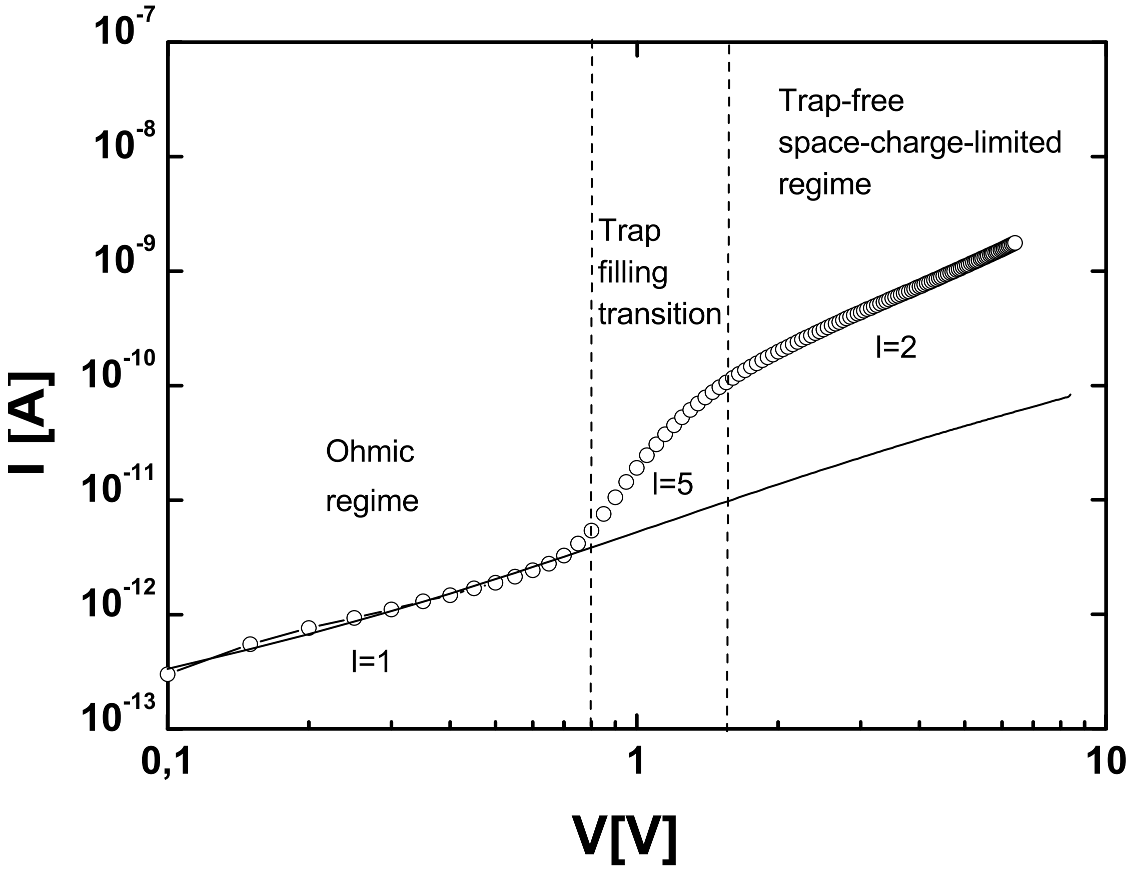
OBJECT of the work: "IMPERFECT INSULATORS"

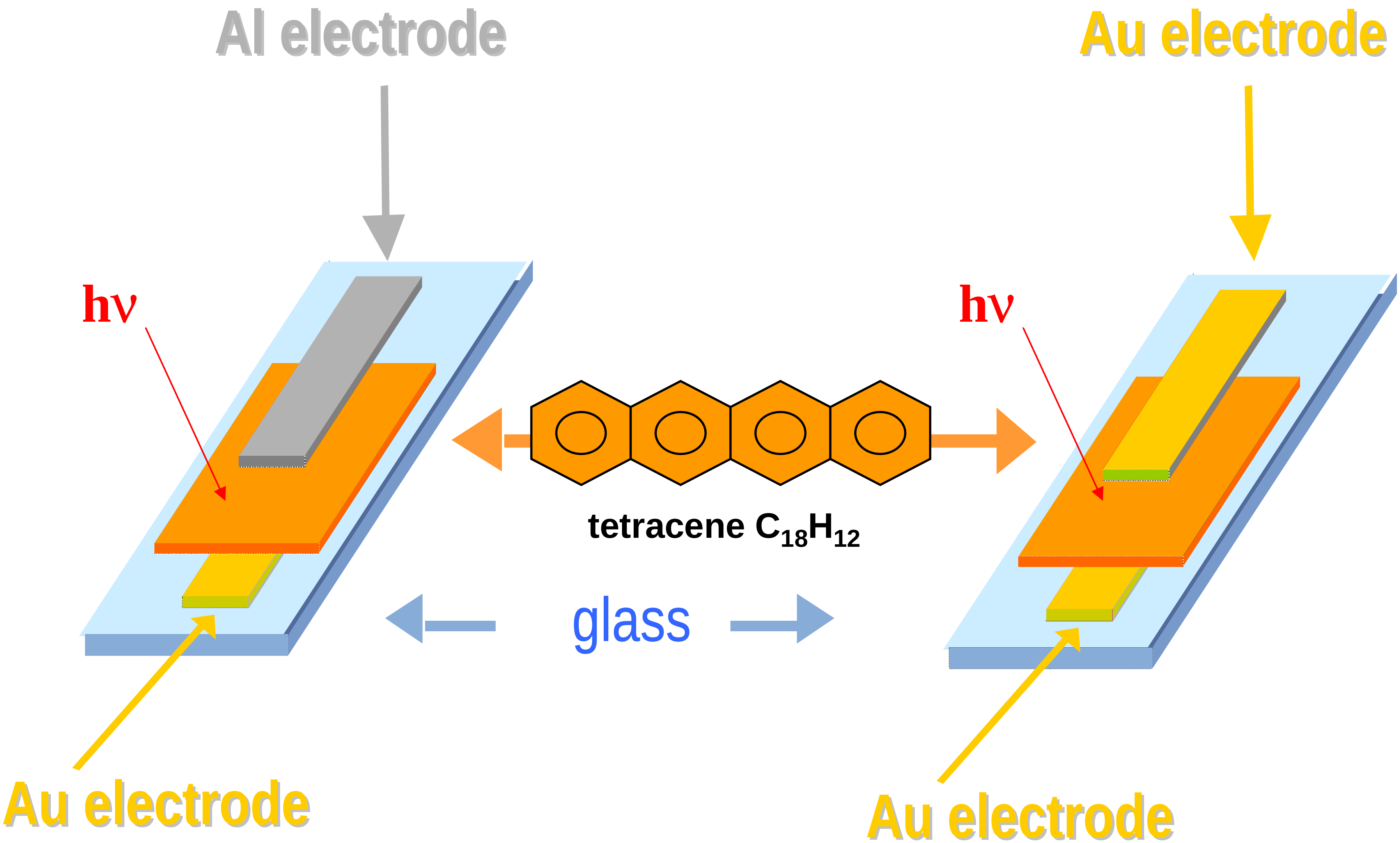


Ideal insulators: transport occurs via carrier injection, as in the vacuum tube. The I-V is quadratic over all the voltage range (Mott-Gurney Law)

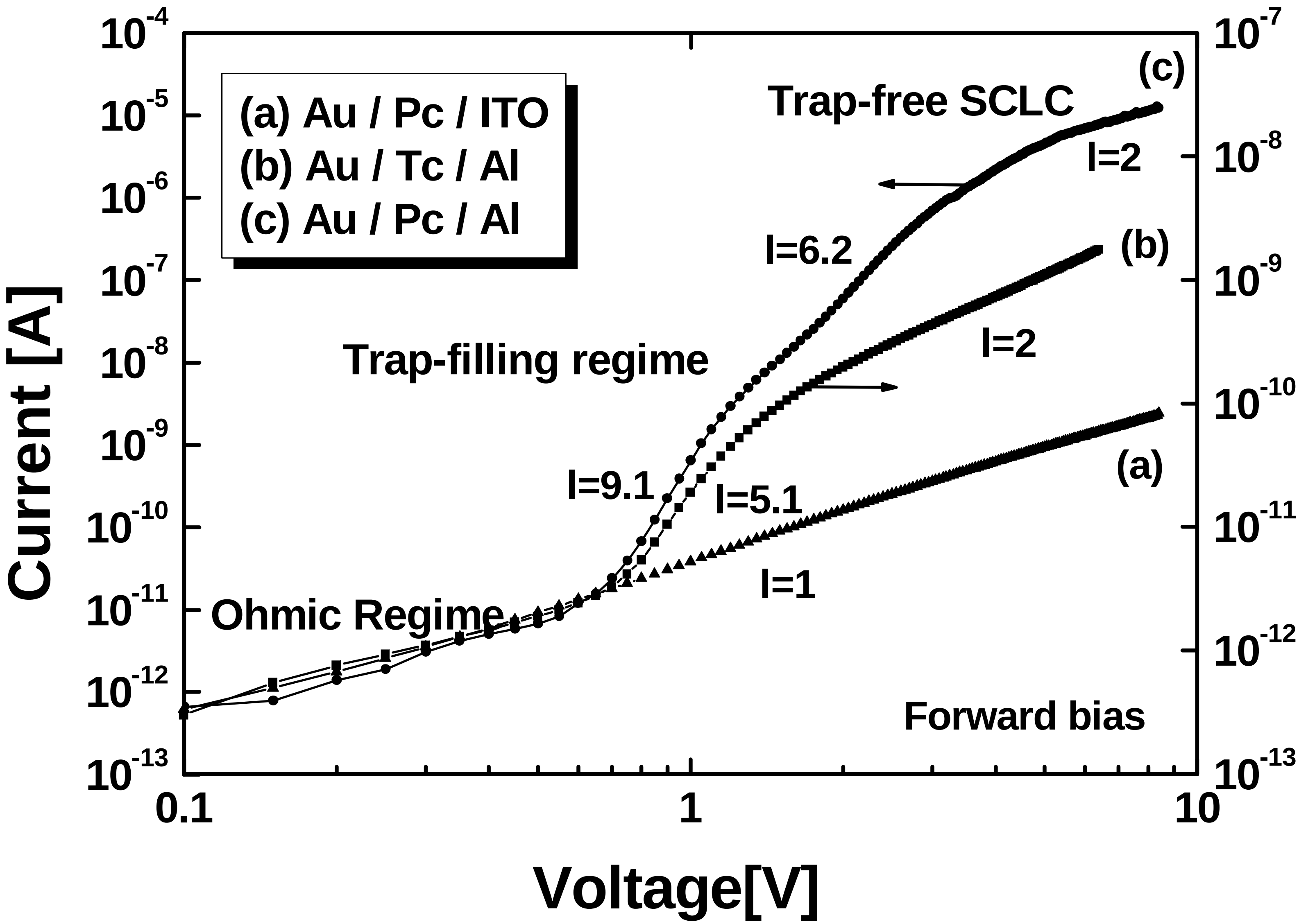
Real insulators: shallow and deep defects store/realease charge carriers which take part with an ohmic component in the transport process

AIM of the work: use noise analysis to gain insights in the interplay between ohmic and space-charge limited current (SCLC) regimes

Samples: pentacene $C_{22}H_{14}$ and tetracene $C_{18}H_{12}$ polycrystalline layers



Space-Charge Limited Current



OHMIC REGIME

$$J_{\Omega} = \frac{e\mu nV}{L}$$

- Linear behavior
- Low Voltage

SPACE-CHARGE LIMITED CURRENT - SCLC REGIME

$$J_{SCLC} = \frac{9\varepsilon\varepsilon_0\mu\Theta V^2}{8L^3}$$

- Mott-Gurney Law
- Quadratic behavior
- High Voltage

TRAP-FILLING TRANSITION –TFT REGIME

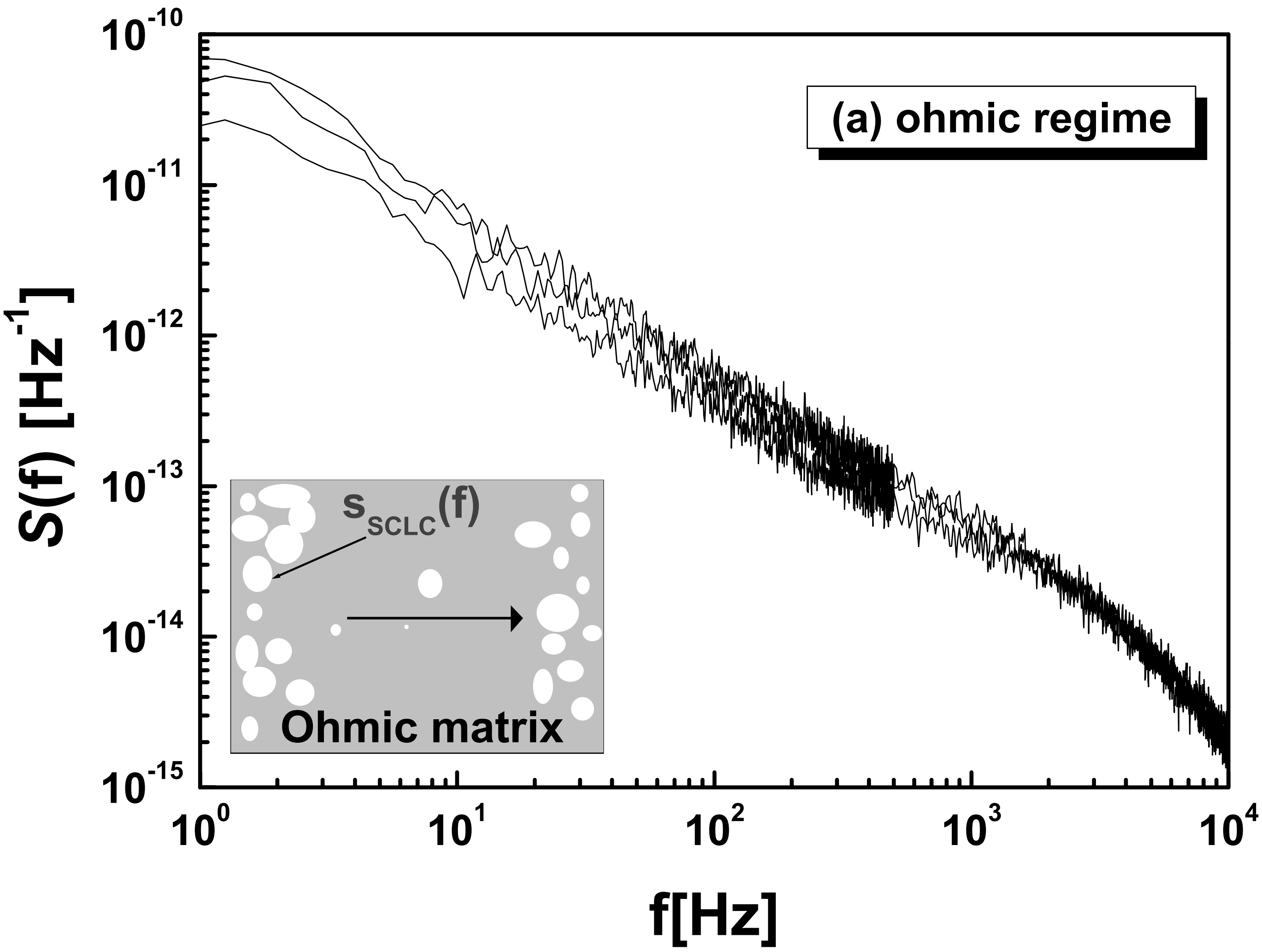
$$J_{TFT} = N_v \mu e^{1-l} \left[\frac{\varepsilon l}{N_t (l+1)} \right]^l \left(\frac{2l+1}{l+1} \right)^{l+1} \frac{V^{l+1}}{L^{2l+1}}$$

Mark-Helfrisch Law

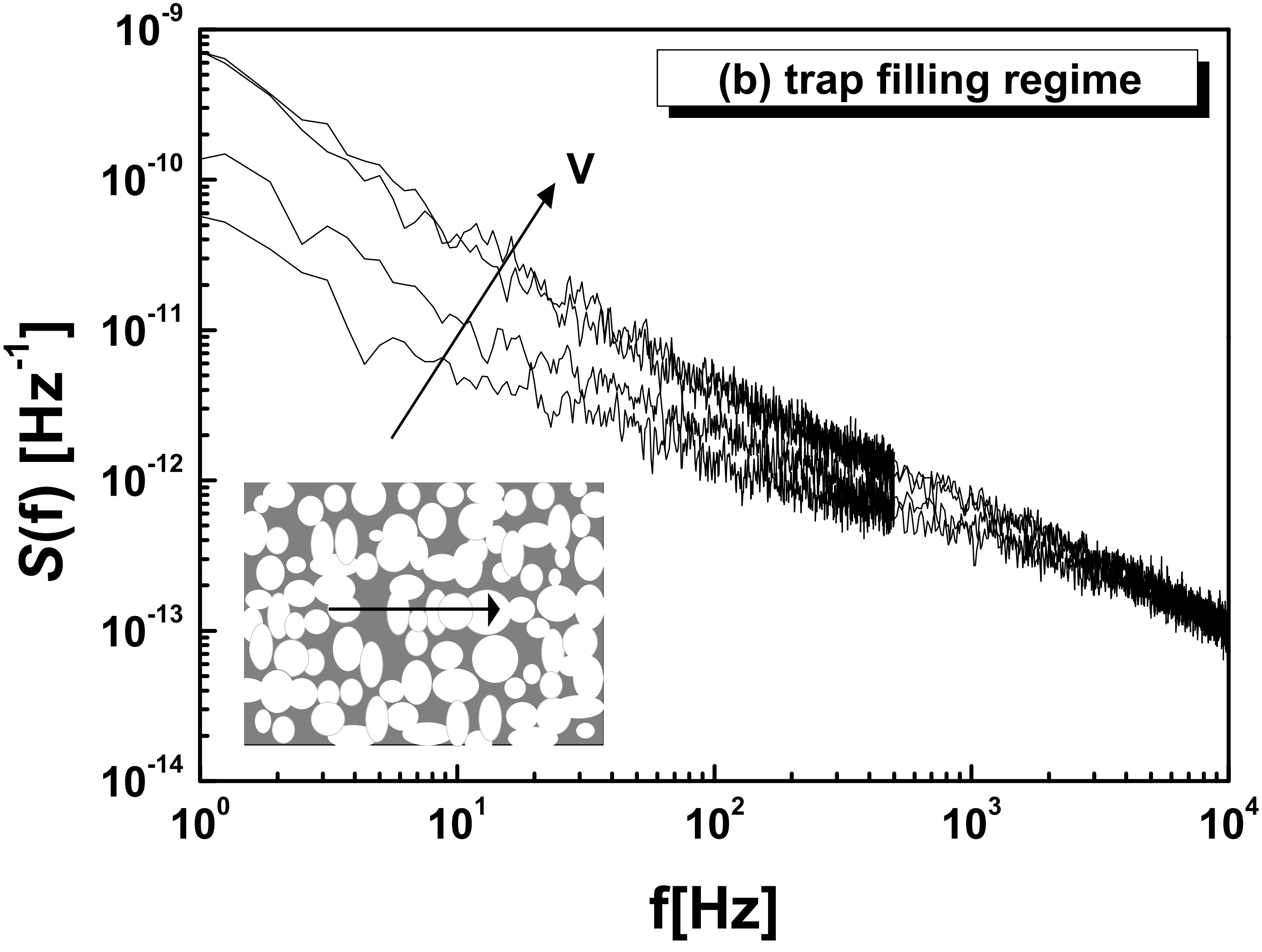
Steep Current Increase

IntermediateVoltage

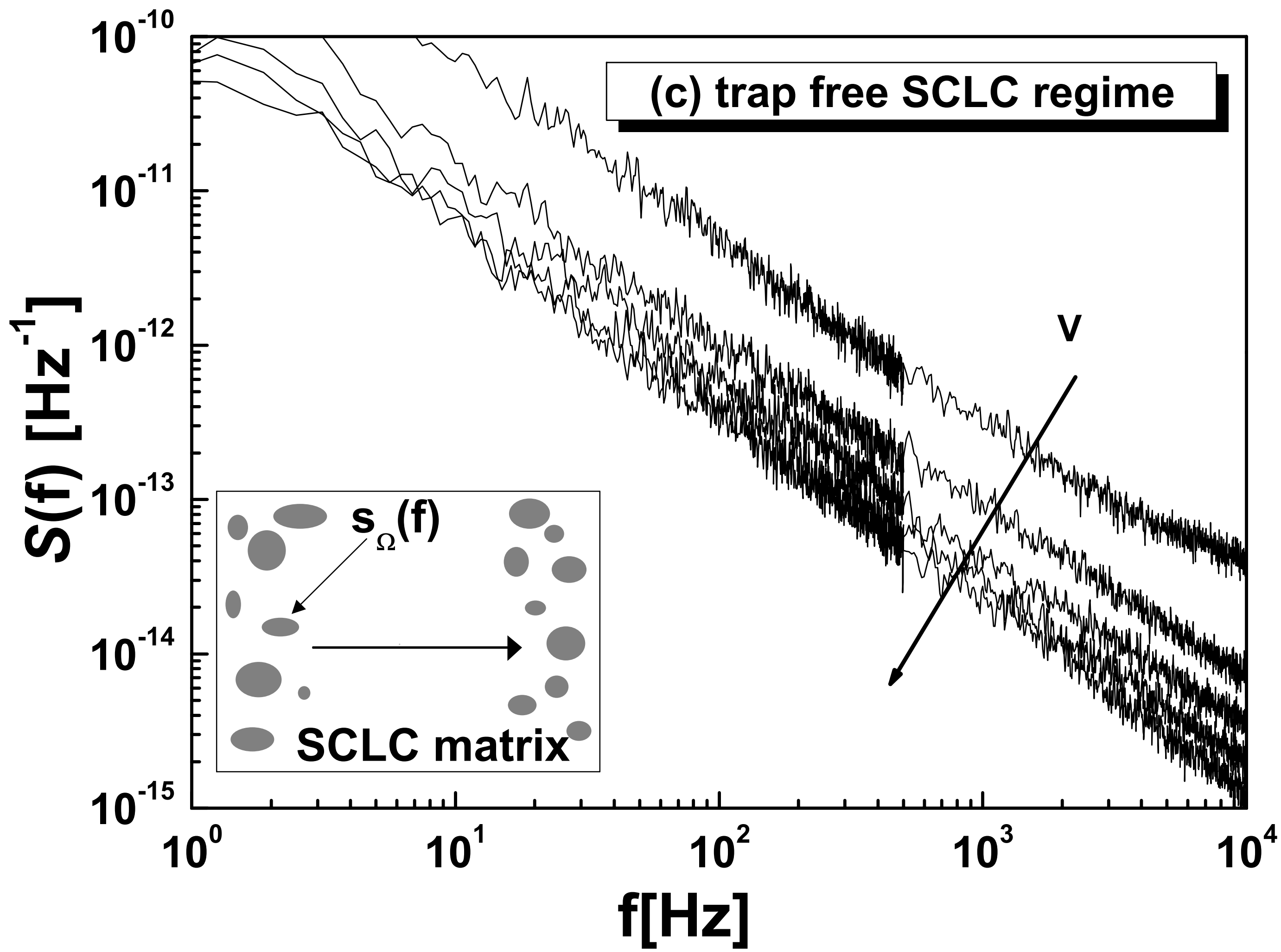
OHMIC REGIME: Relative Current Noise Spectral Density



TRAP-FILLING: Relative Current Noise Spectral Density

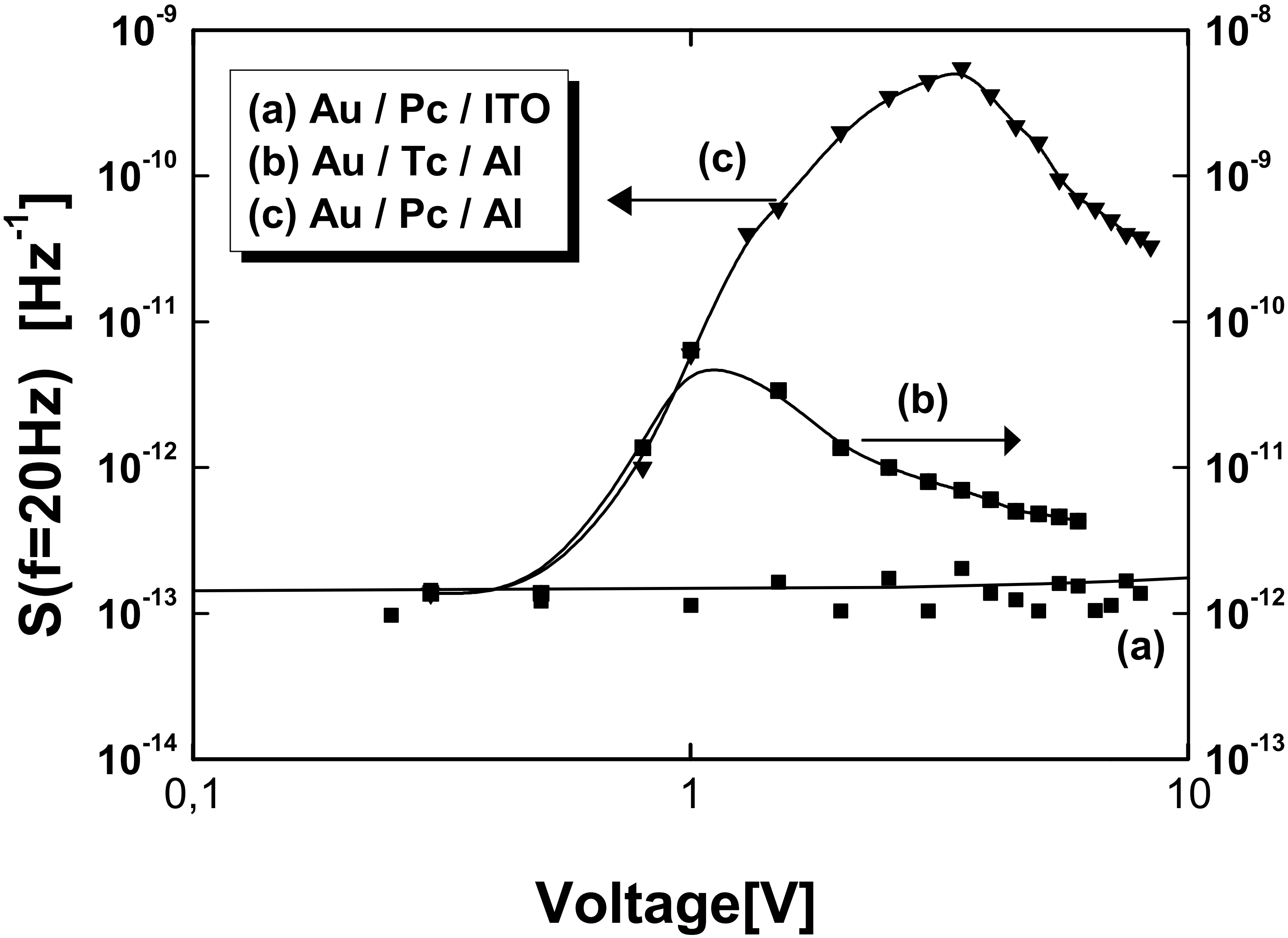


SCLC Regime: Relative Current Noise Spectral Density



FULL VOLTAGE RANGE

Relative Current Noise Spectral Density



Rule of thumb #1 for S

$$S = \frac{S_R(f)}{R^2} = \frac{S_V(f)}{V^2} = \frac{S_I(f)}{I^2} = \frac{V^\gamma}{f^\beta} g(R)$$

g(R) *function*

$g(R) \approx R$ homogeneous systems

$g(R) \approx R^\rho$ inhomogeneous systems (percolation)

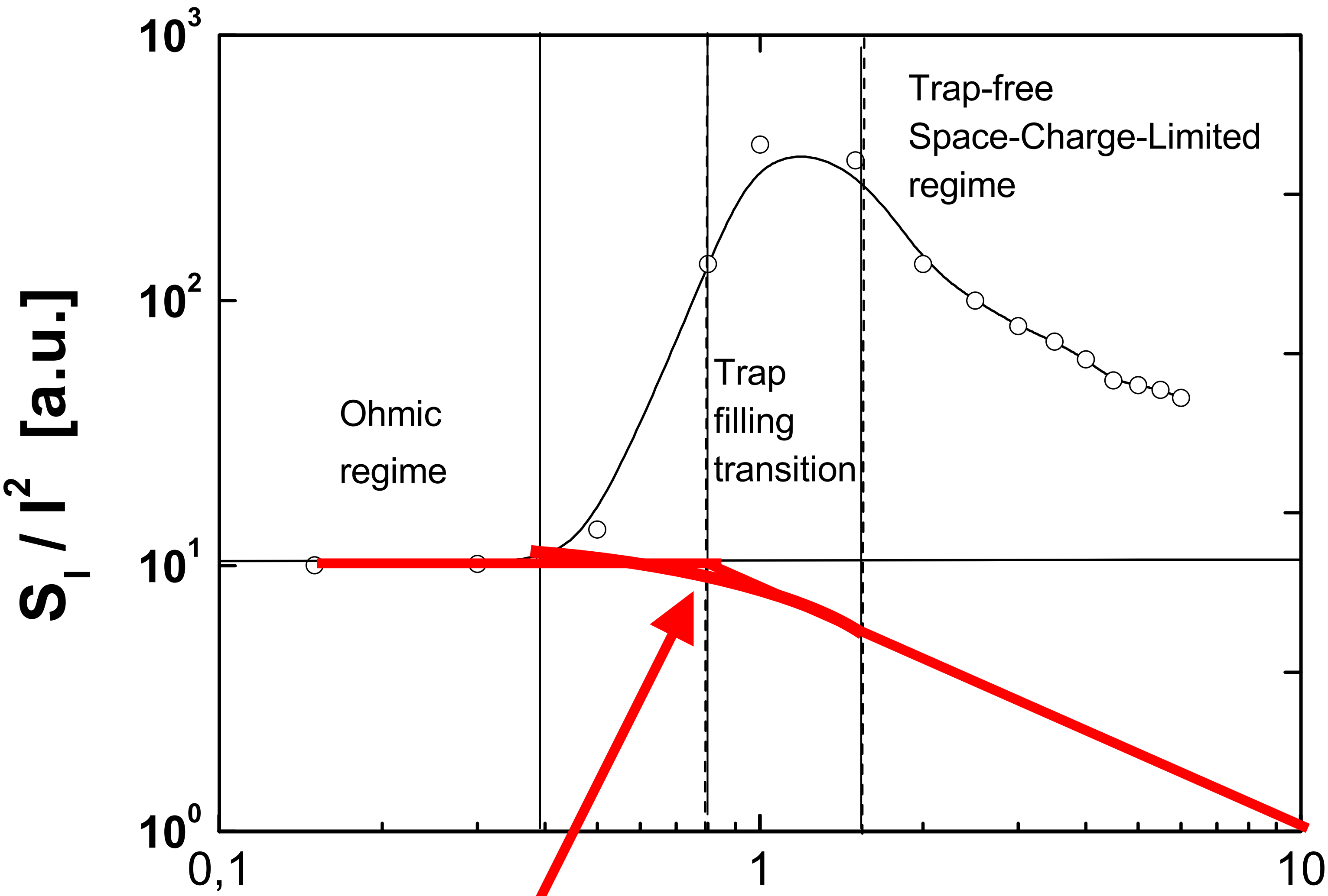
Rule of thumb # 2 for S

γ *exponent*

$$S = \frac{S_R(f)}{R^2} = \frac{S_V(f)}{V^2} = \frac{S_I(f)}{I^2} = \frac{V^{\gamma}}{f^{\beta}} g(R)$$

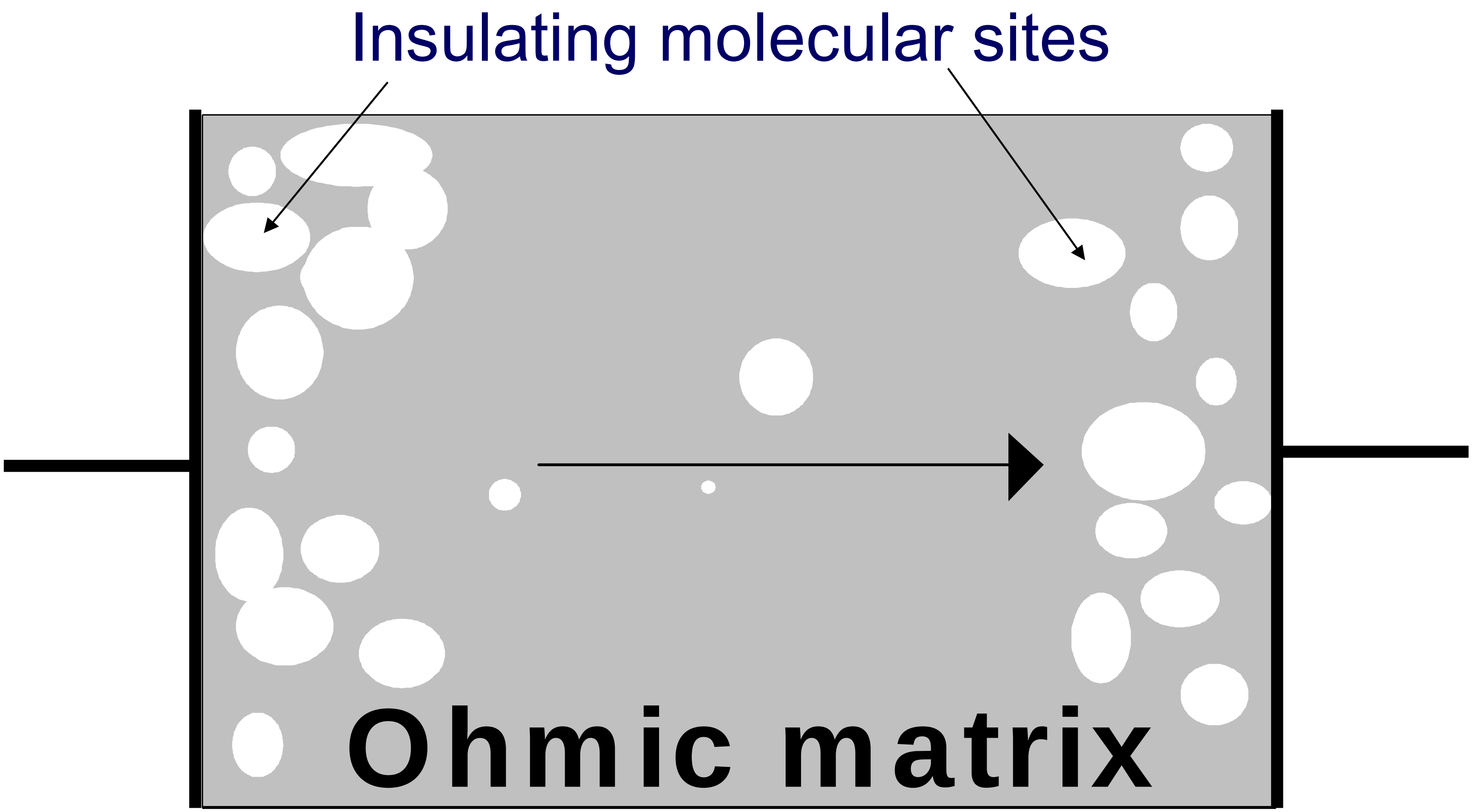
$\gamma \neq 0$ Driven fluctuations

$\gamma = 0$ Equilibrium Resistance fluctuations

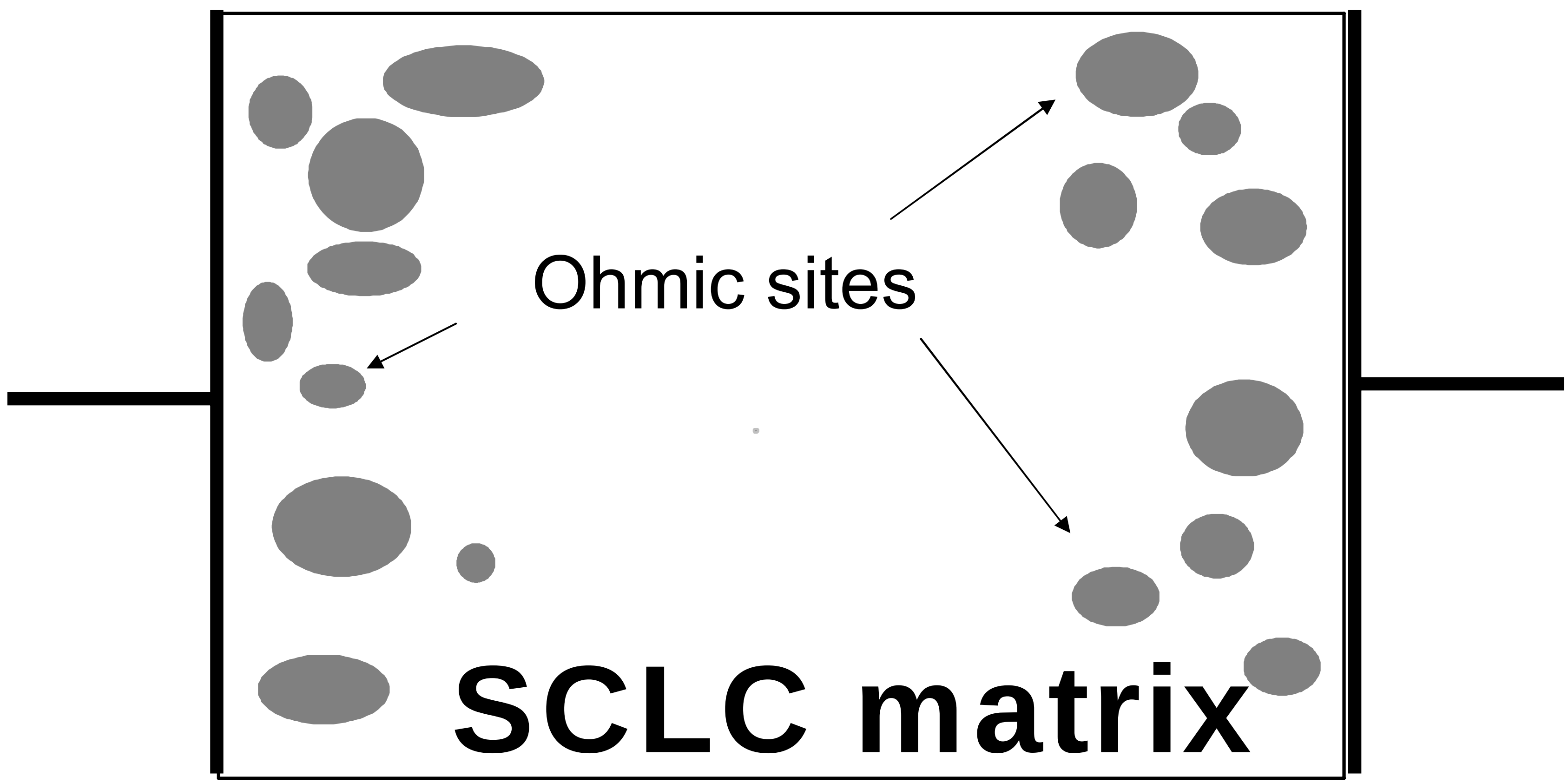


Behavior expected in the absence of percolation (i.e. linear superposition of the two sources of fluctuations)

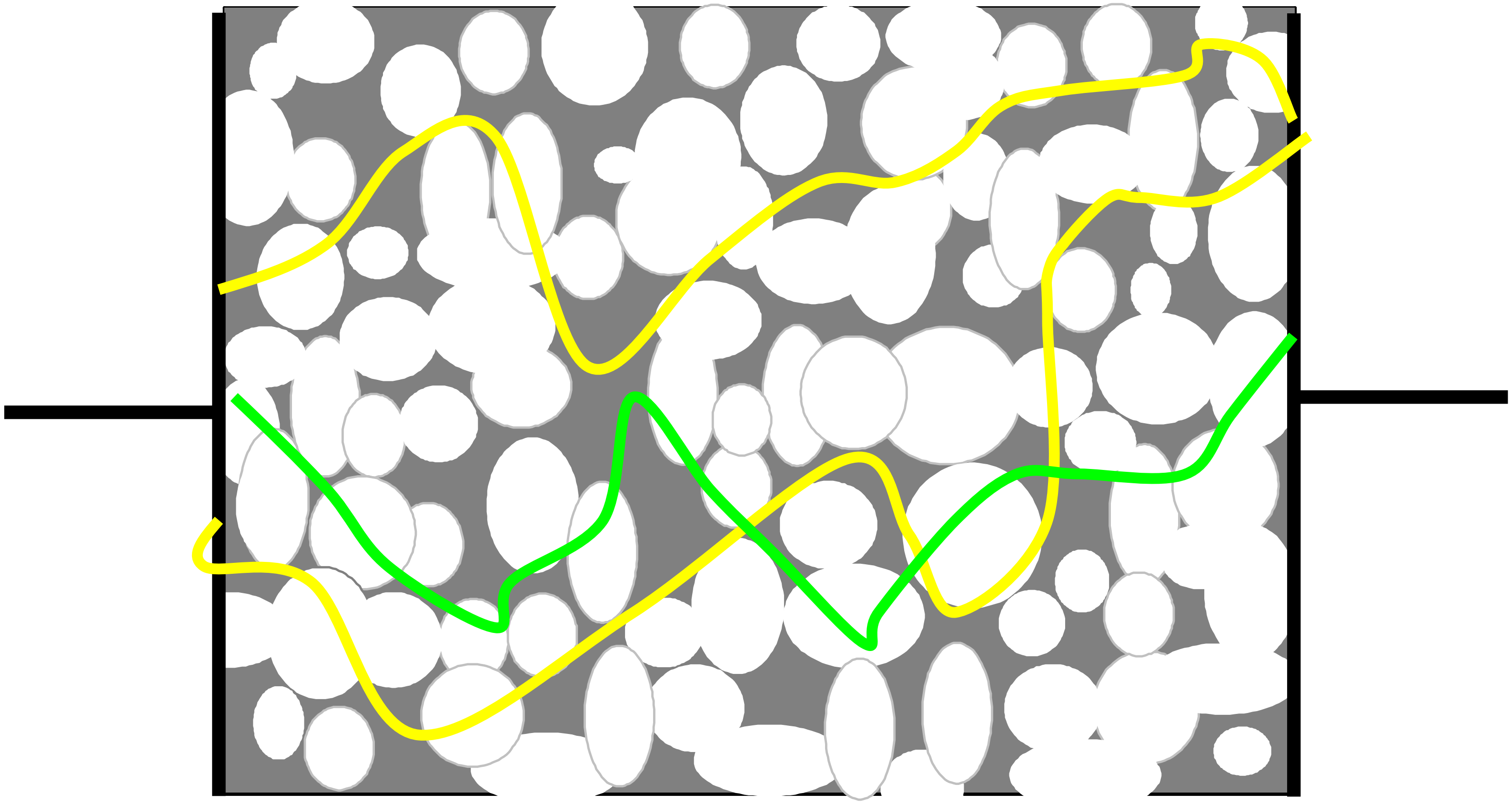
Ohmic Regime: the system can be viewed as a mostly ohmic matrix (grey) with embedded insulating sites (white) .



Space-Charge Limited Current (SCLC) Regime: the system can be viewed as a mostly insulating SCLC matrix (white) with embedded ohmic sites (grey)



Trap-filling regime: the system can be viewed as a disordered matrix with embedded insulating and ohmic sites forming intricate paths.



Percolation Model

Resistance

$$R = \frac{1}{I^2} \sum_{\alpha} r_{\alpha} i_{\alpha}^2$$

Relative Noise Power Spectral Density

$$S(f) = s_{\Omega}(f) \frac{\sum_{\alpha} i_{\alpha}^4}{\left(\sum_{\alpha} i_{\alpha}^2 \right)^2}$$

Percolation Model

Resistance:

$$R \propto \Delta\phi^{-t} = (\phi - \phi_c)^{-t}$$

Relative Noise Power Spectral Density:

$$S \propto \Delta\phi^{-k} = (\phi - \phi_c)^{-k}$$

ϕ: Conductive fraction ϕ_c :Percolative threshold

$$\Delta\phi \propto \frac{n - n_t}{N_v} = \frac{n}{N_v}\left(1 - \frac{n_t}{n}\right)$$

n : quasi-thermal equilibrium free carrier density

n_t : quasi-thermal equilibrium filled trap density

$$n = N_v \exp[-(E_v - E_F)/kT]$$

$$n_t = \frac{N_t}{1 + \frac{1}{g}\exp[-(E_F - E_t)/kT]}$$

$$\boxed{\frac{n_t}{n} = \frac{2N_t \exp\left[-(E_t - E_v)/kT\right]}{N_v}}$$

What happens at the percolation threshold?

$$\Delta\phi \rightarrow 0 \qquad R \propto \Delta\phi^{-t} \rightarrow \infty \qquad S \propto \Delta\phi^{-k} \rightarrow \infty$$

In our case:

$$\Delta\phi \rightarrow 0 \qquad 1 - \frac{n_t}{n} \rightarrow 0 \qquad n_t \rightarrow n$$

i.e.

$$2N_t \exp\left[-(E_t - E_v)/kT\right] \rightarrow N_v$$

i.e. the increase of N_t (additional defect levels)

CONCLUSIONS

- Current noise is investigated in organic materials exhibiting SCLC I-V characteristics.

- These materials are representative of the class of disordered insulators ("imperfect insulators")

- The system has been described as a mixture of conducting (ohmic) and insulating (SCLC) molecular sites, with relative composition driven by the applied bias.

- The noise has been modelled in the framework of classical percolation theory