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Measurements of RF noise in InGaAs/InAlAs recessed diodes: Signatures of shot-noise suppression

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Shot Noise

Shot-noise $S_I=2qI$ is related to the discrete character of the electronic charge and is usually observed in electronic devices when carrier transport is ballistic or is limited by an energy barrier (Schottky diodes, tunnel diodes…)

Shot-noise $S_I=\gamma\ 2qI$

Fano Factor $\gamma = S_I / 2qI$

- Uncorrelated carriers → *full* shot noise $\gamma = 1$
- Correlated carriers →
  - *suppressed* shot noise $\gamma < 1$
  - *enhanced* shot noise $\gamma > 1$

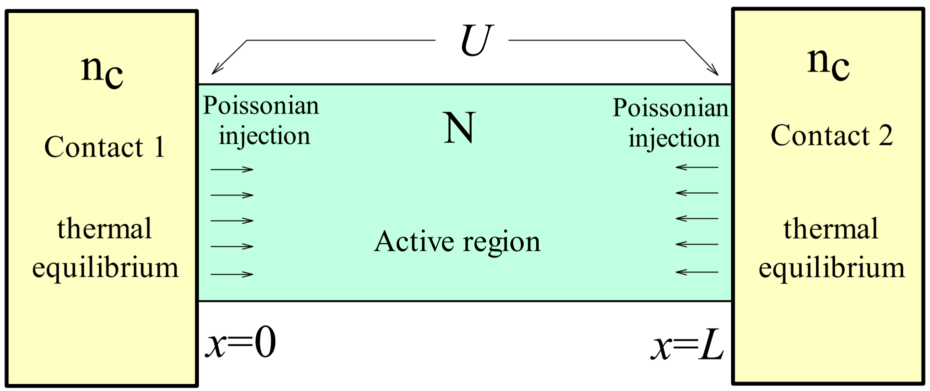
Origin of correlations: Pauli exclusion principle (degenerate semiconductors)
Long-range Coulomb interaction (strong space-charge effects)

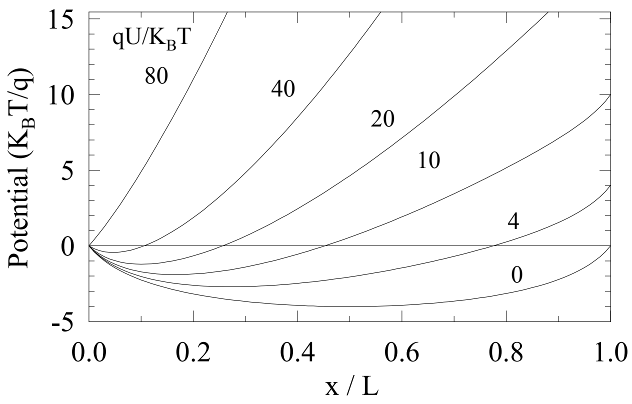
↓

The **measurement** of shot noise and the value of its corresponding Fano Factor can provide valuable insight about the transport dynamics inside semiconductor devices

Shot Noise

Ballistic diode

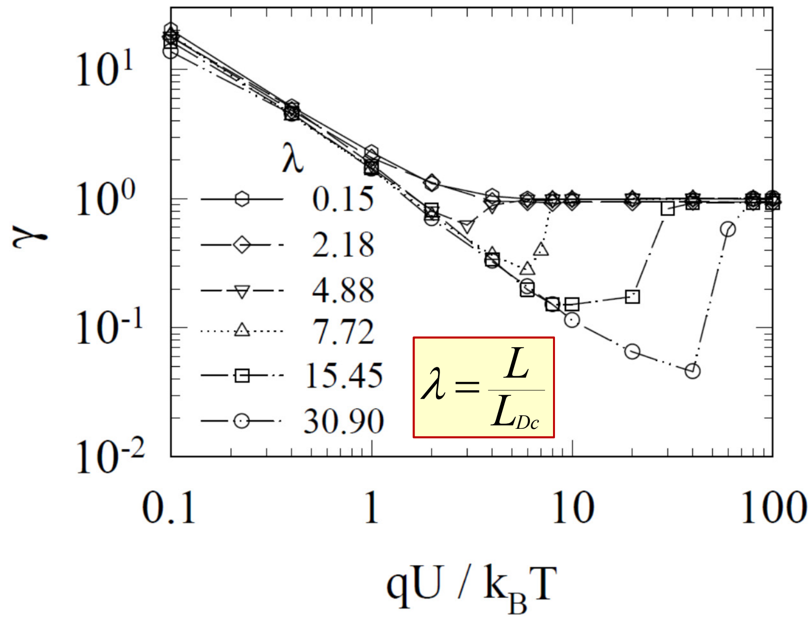




Presence of a barrier that disappears when voltage is increased

Shot noise suppression due to long range Coulomb correlations

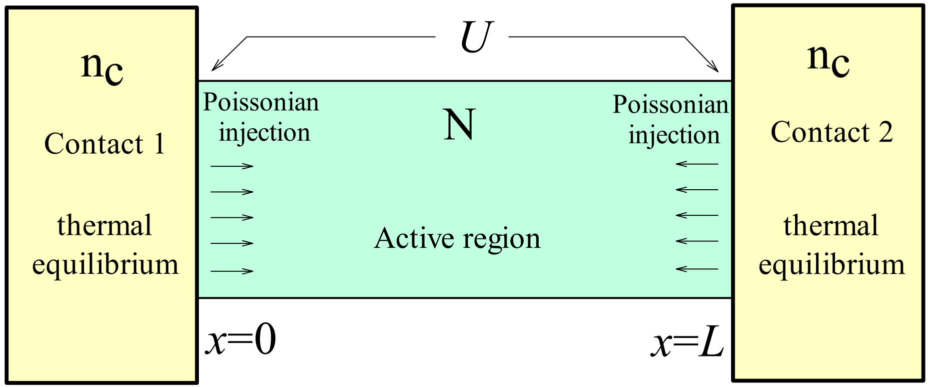
high λ ⇨ important space-charge effects

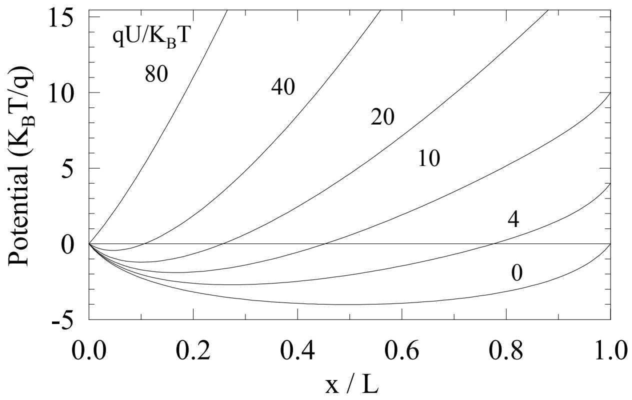


Full shot noise is recovered when the barrier disappears

Shot Noise

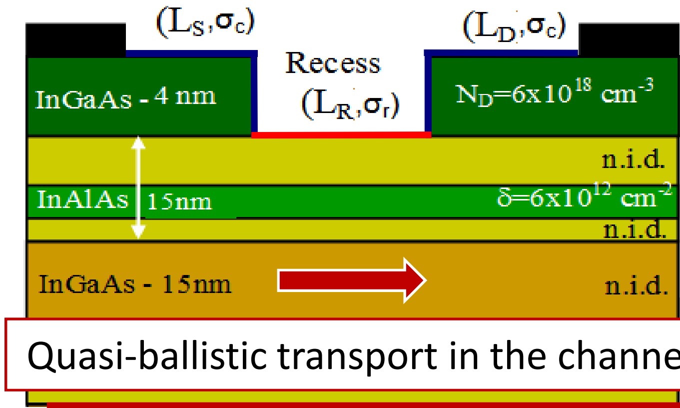
Ballistic diode





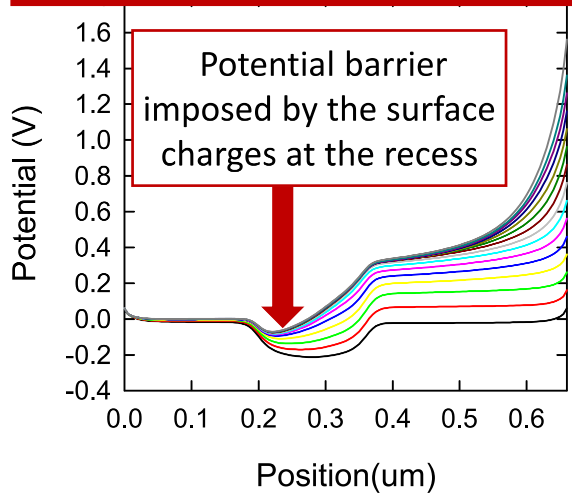
Presence of a barrier that disappears when voltage is increased

Recessed planar diodes=Slot diodes (ungated HEMTs)



Quasi-ballistic transport in the channel

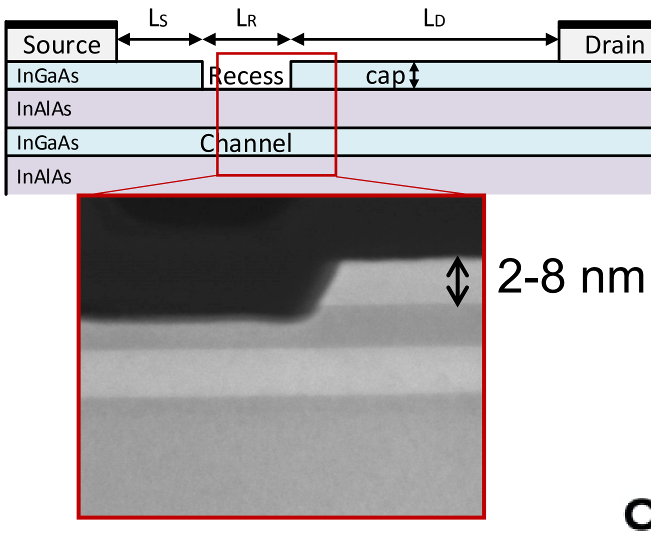
Shot noise suppression expected



Potential barrier imposed by the surface charges at the recess

Slot diodes: fabrication

Slot diodes with different geometries have been fabricated and characterized



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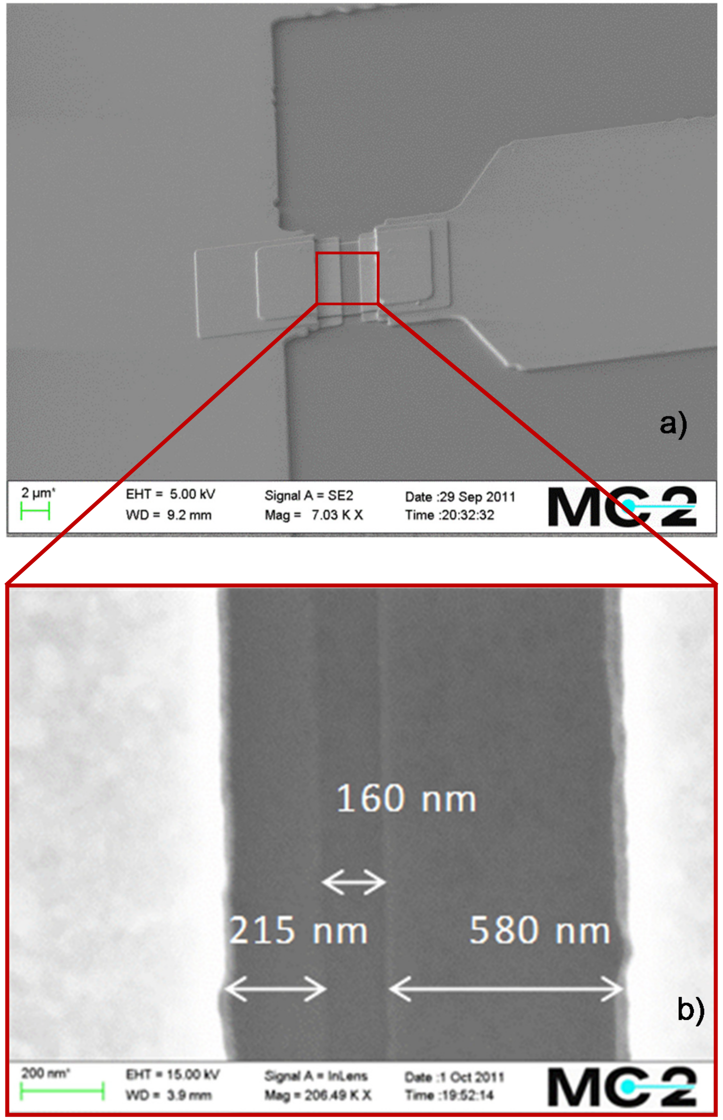
Parameter	Reference design [nm]	Tested range [nm]
L_s	200	200-800
L_r	200	200-800
L_d	550	300-1000

+ **Diodes without recess**



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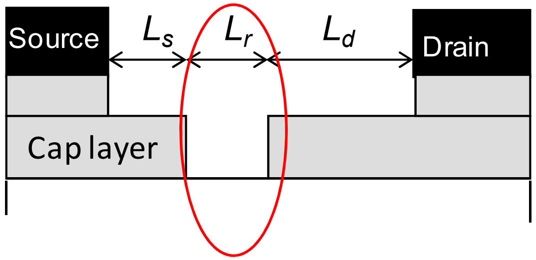
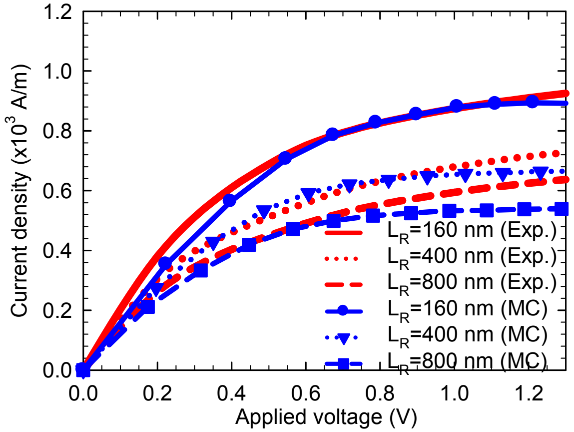
Slot diodes: Monte Carlo simulations

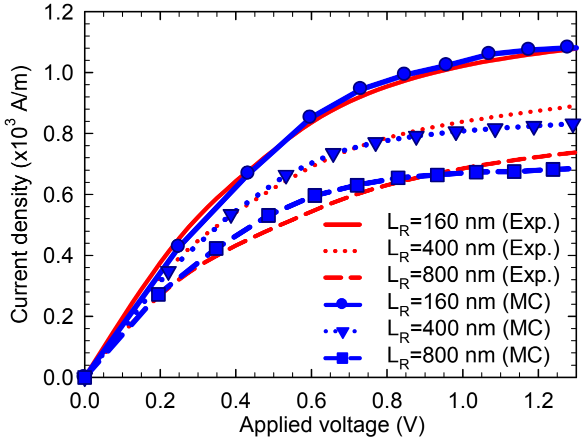
L_s = 200nm
L_d = 550nm
160nm<L_r<800nm



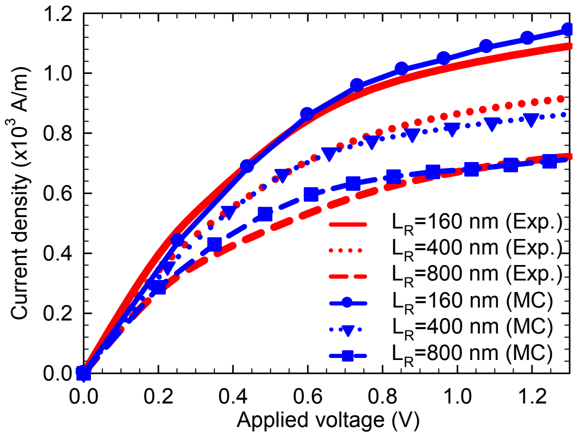
+ **Contact Resistance** (0.35 Ω.mm)



Batch C7, type 6 - **Cap 2nm**



Batch C7, type 2 - **Cap 4nm**

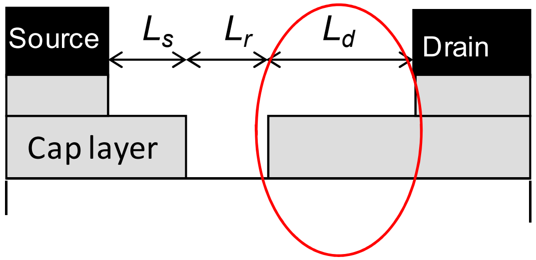


Batch C7, type 5 - **Cap 8nm**

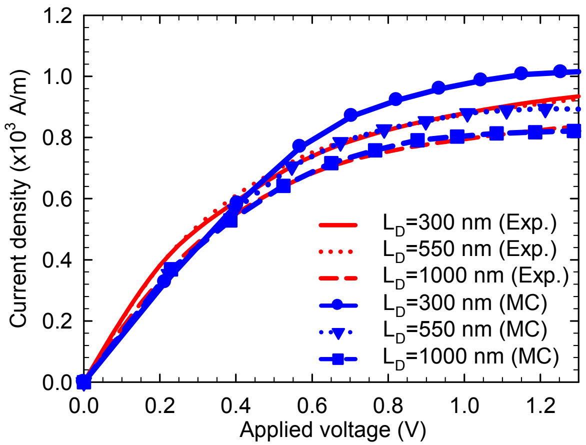
MC simulations reproduce the experimental DC curves and their dependence on L_s, L_r and L_d by adjusting the values of the surface charges and including the ohmic contact resistances

Slot diodes: Monte Carlo simulations

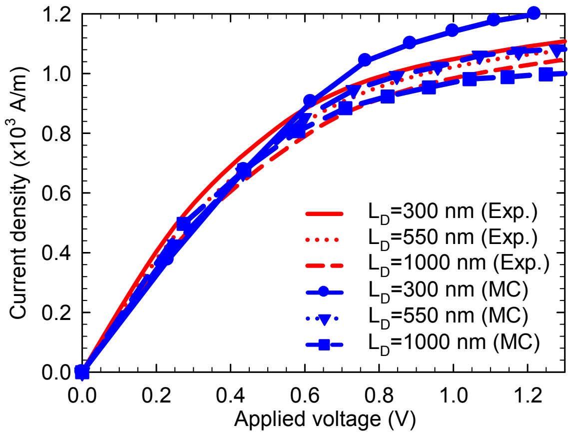
L_s = 200nm
L_r = 160nm
300nm<L_d<1000nm



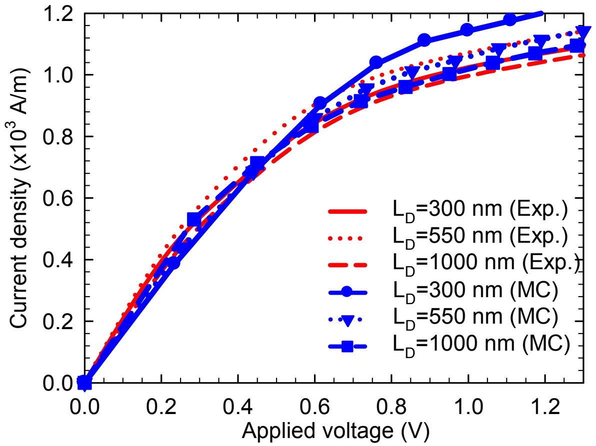
+ **Contact Resistance** (0.35 Ω.mm)



Batch C7, type 6 - **Cap 2nm**



Batch C7, type 2 - **Cap 4nm**

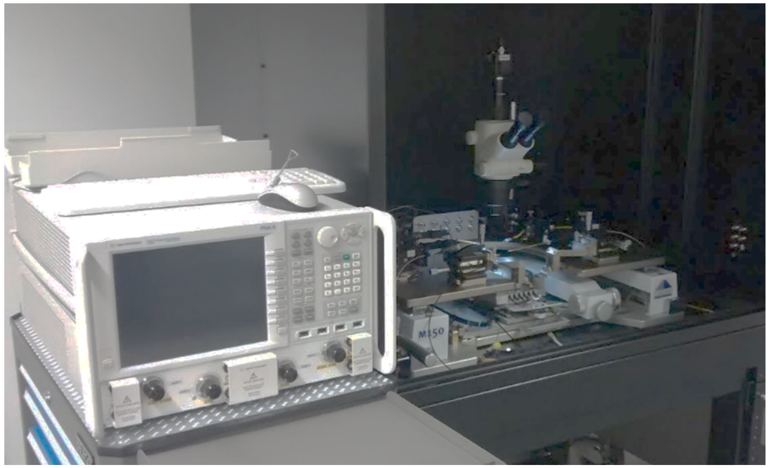


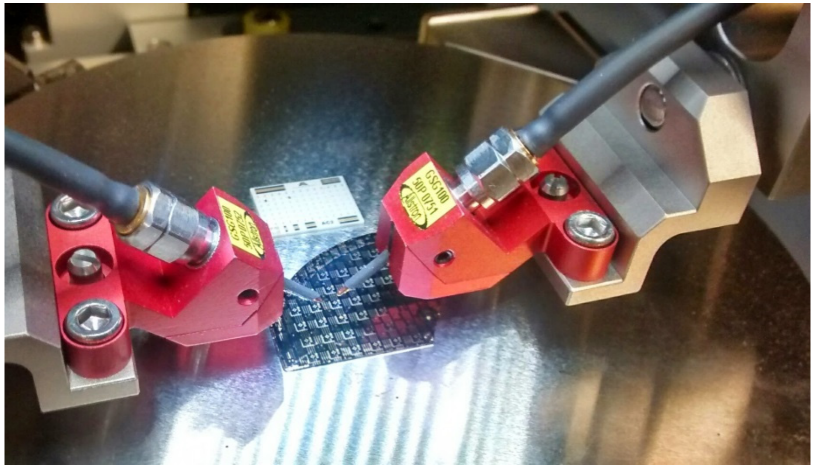
Batch C7, type 5 - **Cap 8nm**

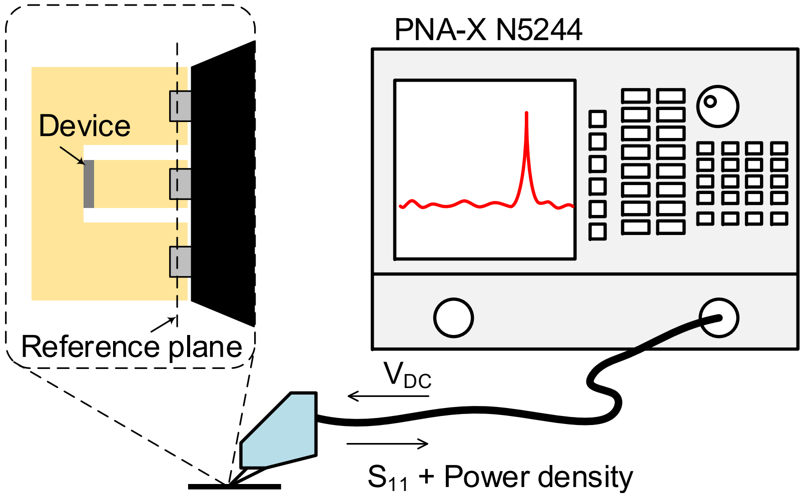
MC simulations reproduce the experimental DC curves and their dependence on L_s, L_r and L_d by adjusting the values of the surface charges and including the ohmic contact resistances

Noise measurements

Measurements performed on wafer with a VNA Agilent PNA-X N5244 (with dedicated receivers for high sensitivity noise power measurements) in the range between **20 and 30 GHz**.



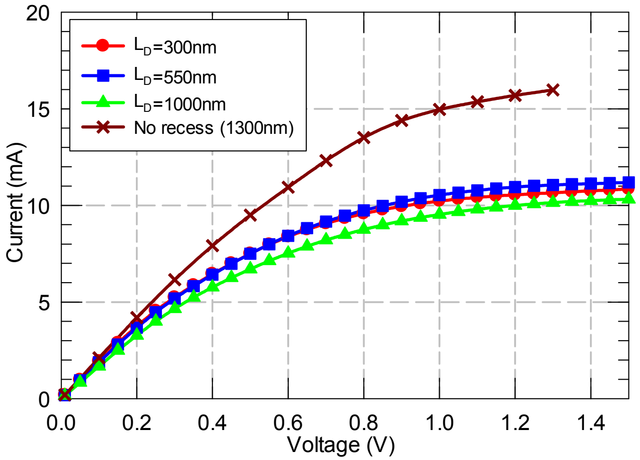


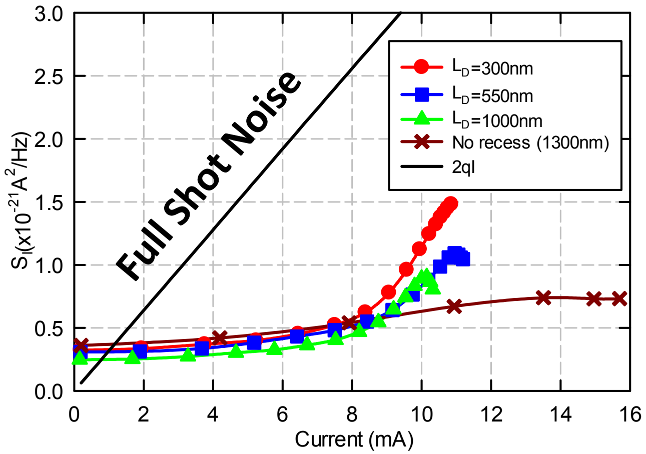


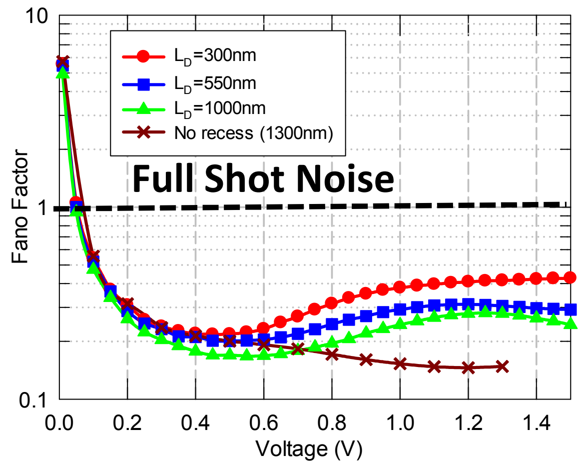
Noise measurements

L_s = 200 nm, L_r = 160 nm, L_d = 300, 500, 1000 nm

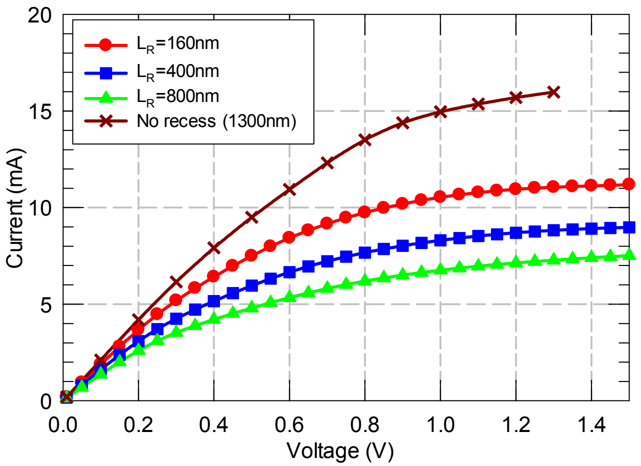
x Non-recessed diode with L = 1.3 μm

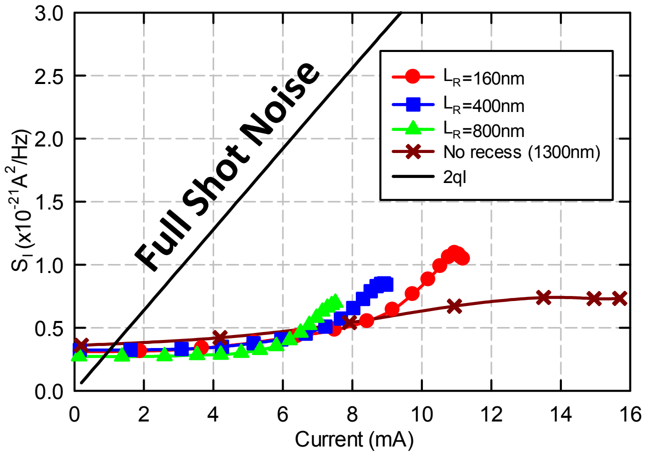


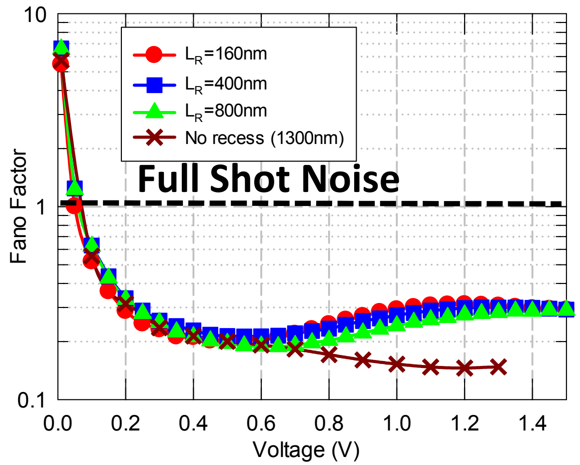




L_s = 200 nm, L_d = 550 nm, L_r = 160, 400, 800 nm





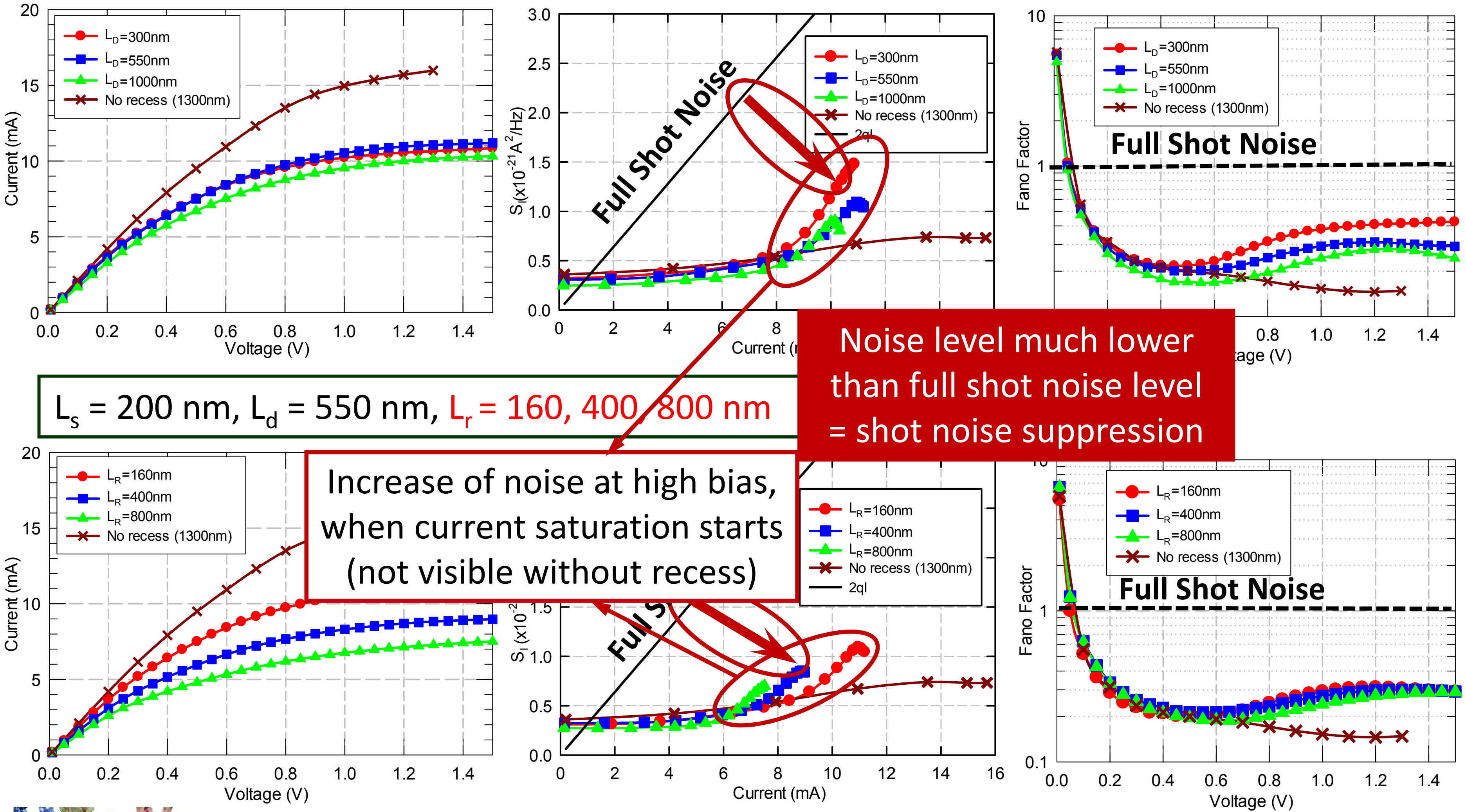


Noise measurements

L_s = 200 nm, L_r = 160 nm, L_d = 300, 500, 1000 nm

x Non-recessed diode with L = 1.3 μm

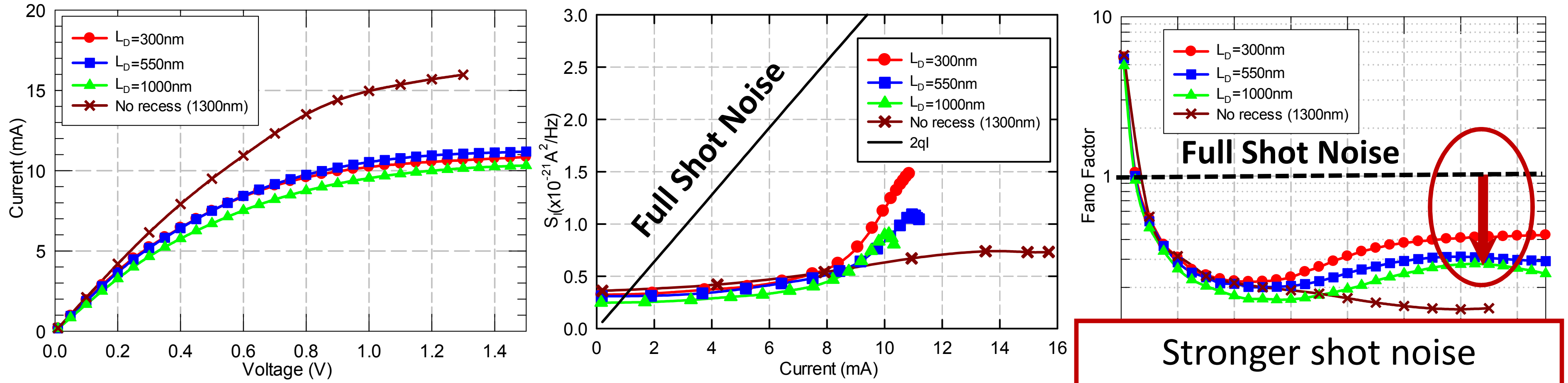
L_s = 200 nm, L_d = 550 nm, L_r = 160, 400, 800 nm



Noise measurements

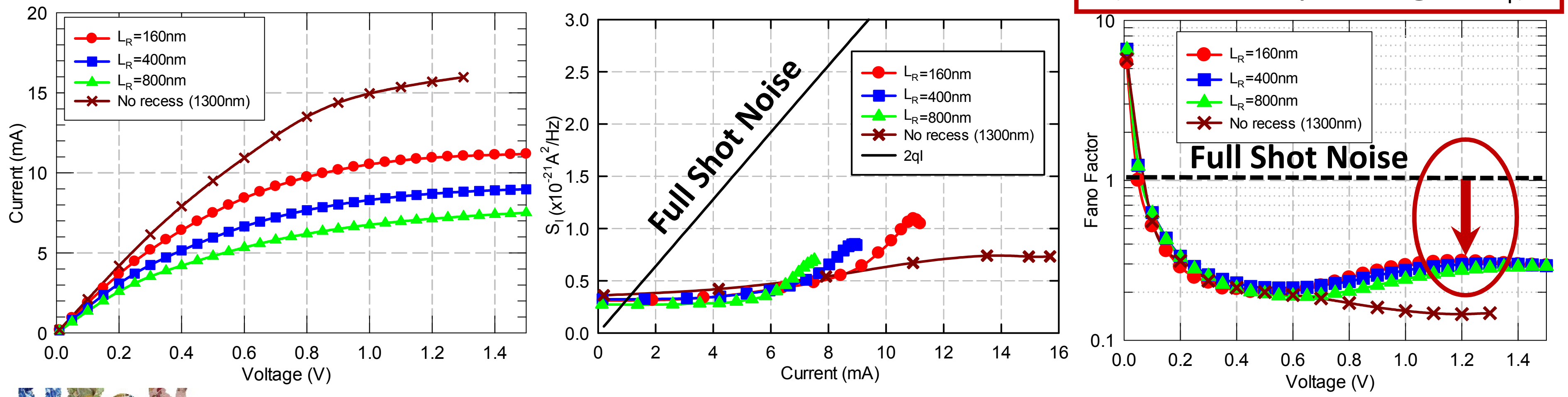
L_s = 200 nm, L_r = 160 nm, L_d = 300, 500, 1000 nm

x Non-recessed diode with L = 1.3 μm



Stronger shot noise suppression for longer L_d (and not depending on L_r)

L_s = 200 nm, L_d = 550 nm, L_r = 160, 400, 800 nm

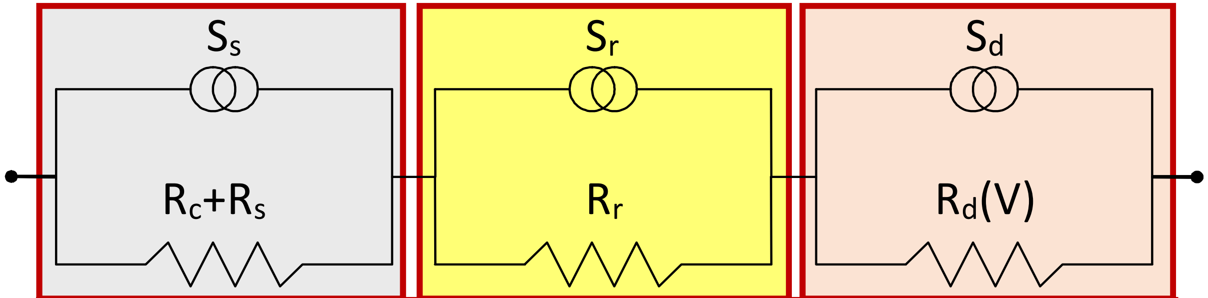


Noise models: discussion

- ✓ Barrier limited transport → Shot noise
- ✓ $S_r = F \cdot 2qI$

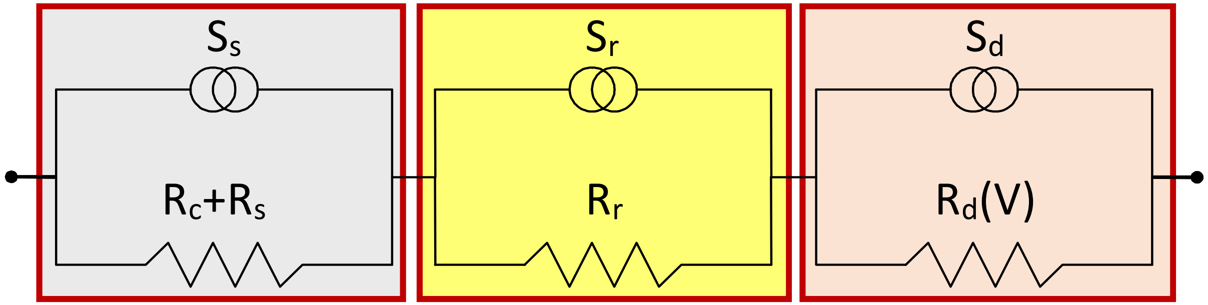
- ✓ Ohmic region → Thermal noise
- ✓ Always at equilibrium $S_s = \dfrac{4K_BT}{R_c+Rs}$

- ✓ Ohmic region → Thermal noise
- ✓ Bias dependent resistance $S_d = \dfrac{4K_BT}{R_d(V)}$



$$S_T = \frac{S_s(R_c+R_s)^2}{(R_c+R_s+R_r+R_d)^2} + \frac{S_r(R_r)^2}{(R_c+R_s+R_r+R_d)^2} + \frac{S_d(R_d)^2}{(R_c+R_s+R_r+R_d)^2}$$

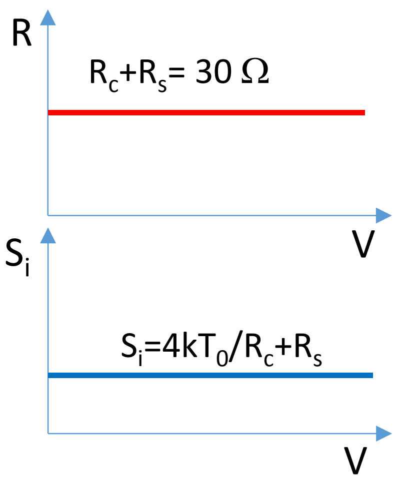
Noise models: discussion



- ✓ $R_c+R_s = 30\ \Omega$
- ✓ $S_s = \dfrac{4K_BT}{R_c+Rs}$ with $T = 300$ K

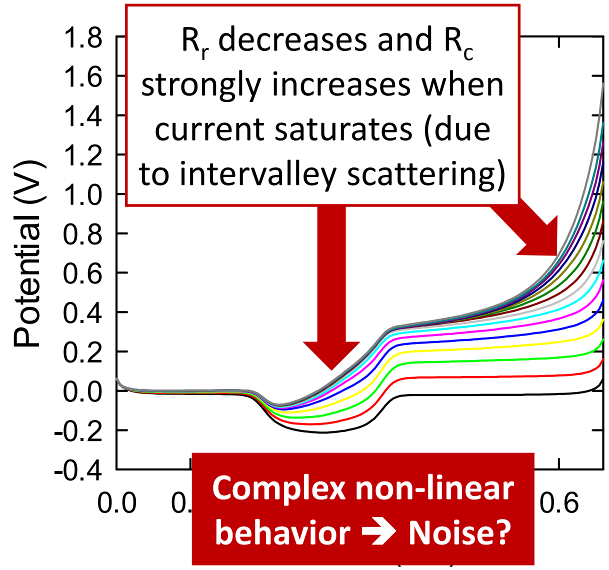
- ✓ $R_r = ?$
- ✓ S_i=F·2ql

- ✓ $R_d = ?$
- ✓ $S_d = \dfrac{4K_BT}{R_d}$ with $T = ?$

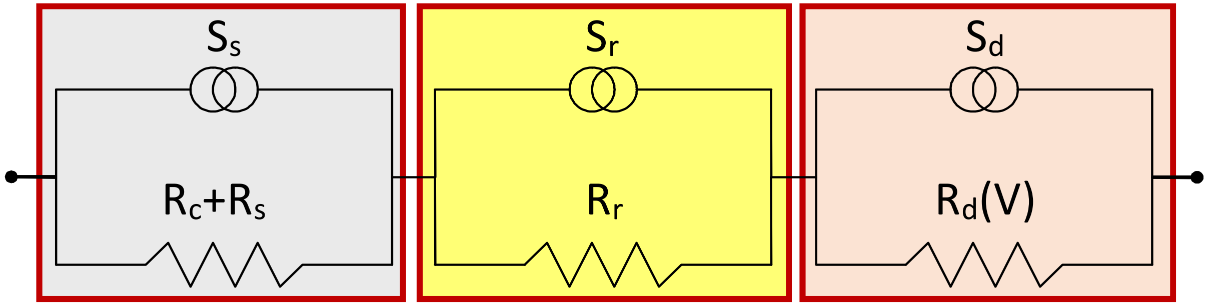


Total resistance is measured $R_T(V)=R_c+R_s+R_r+R_d$ is known

The values of R_r and R_c can be estimated from Monte Carlo simulations



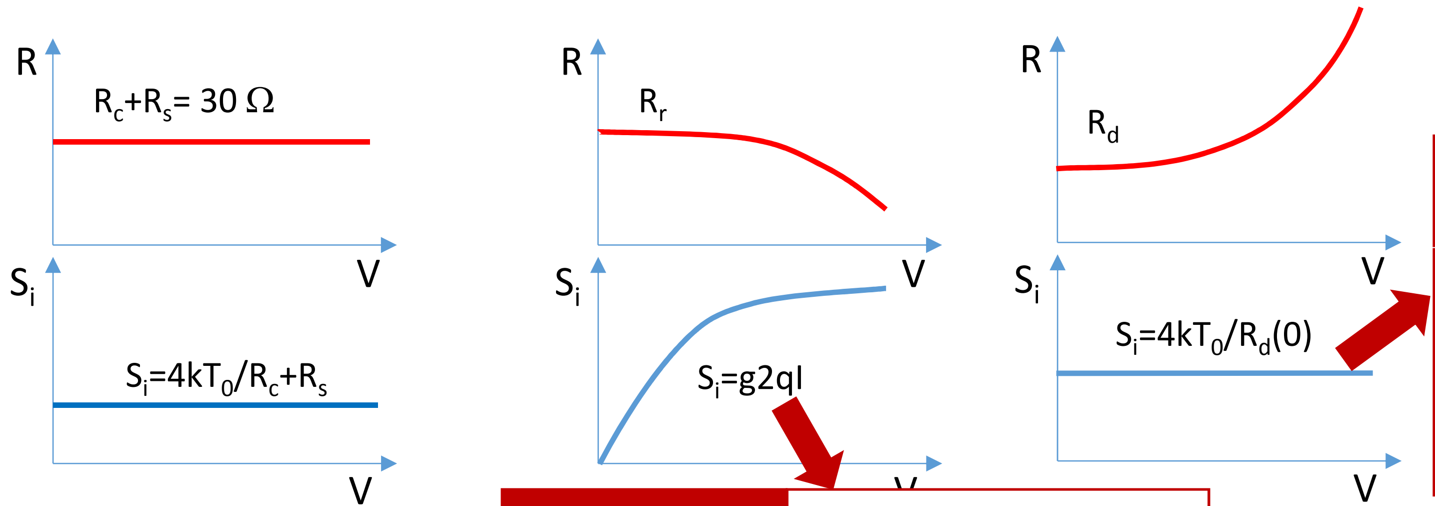
Noise models: discussion



- ✓ $R_c+R_s = 30\ \Omega$
- ✓ $S_s = \dfrac{4K_BT}{R_c+Rs}$ with $T = 300$ K

- ✓ $R_r = ?$
- ✓ $S_i = F\cdot 2qI$

- ✓ $R_d = ?$
- ✓ $S_d = \dfrac{4K_BT}{R_d}$ with $T = ?$



Simplified noise model	Full/suppressed shot noise in the active region

Simplified noise model
Noise in R_d is initially supposed to be constant (equilibrium value of R_d)

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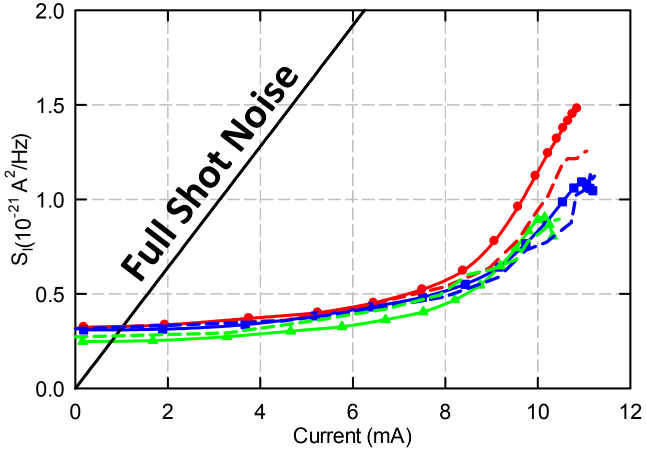
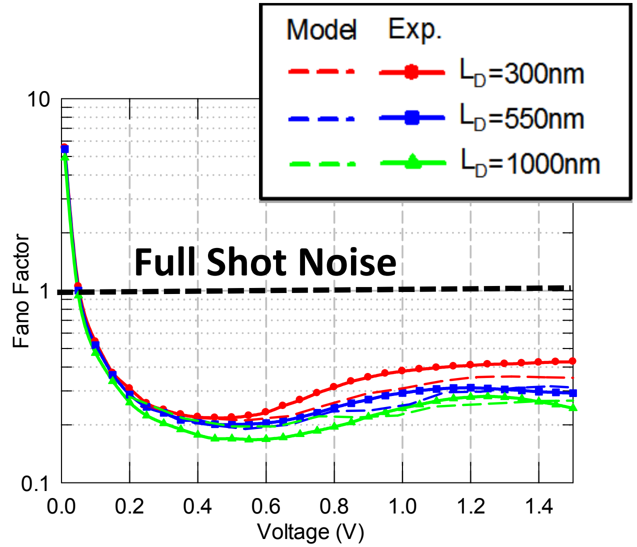
Noise measurements and models

L_s = 200 nm, L_r = 160 nm, L_d = 300, 500, 1000 nm

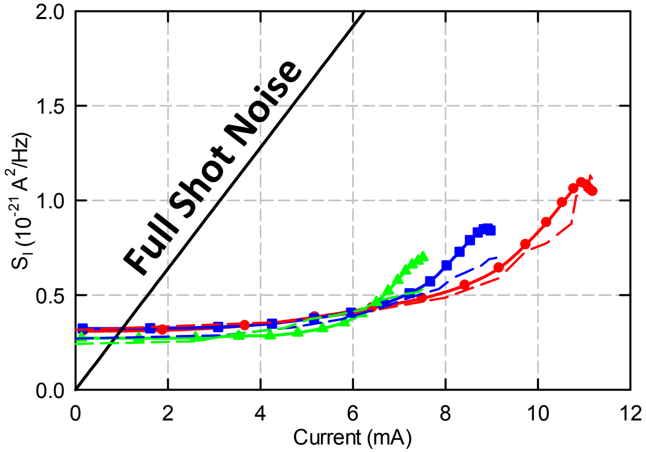
Full shot noise in the active region F=1

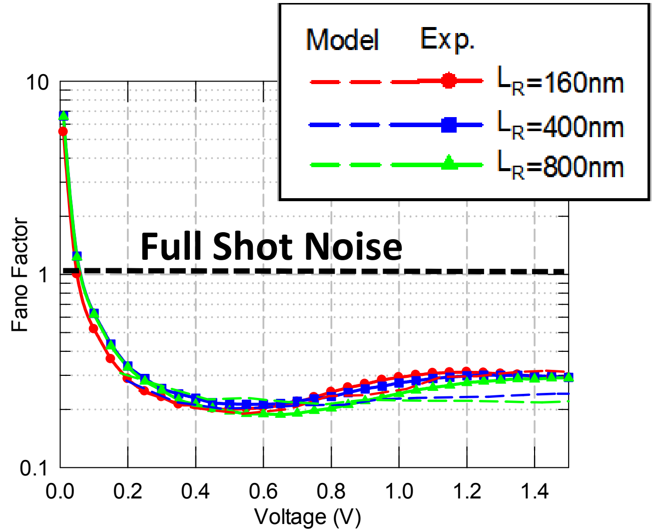




L_s = 200 nm, L_d = 550 nm, L_r = 160, 400, 800 nm

The simplified noise model provide good qualitative agreement with the experimental results (that could be improved by increasing the noise temperature of both contact and drain resistances)



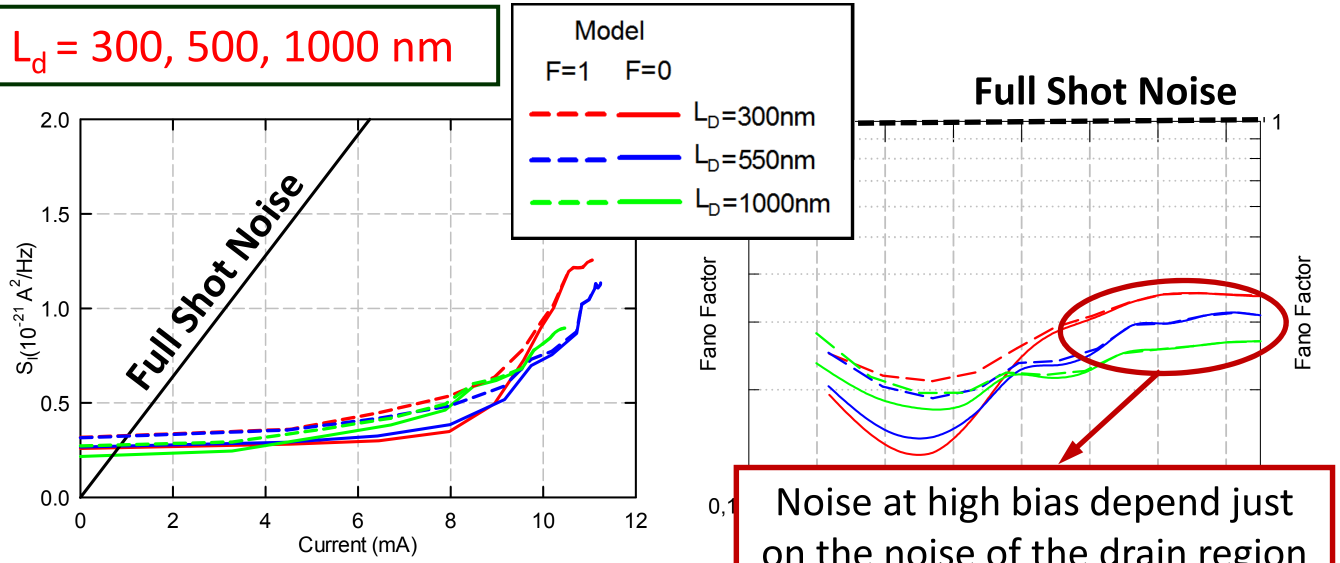


Noise measurements and models

L_s = 200 nm, L_r = 160 nm, L_d = 300, 500, 1000 nm

Full shot noise in the active region F=1

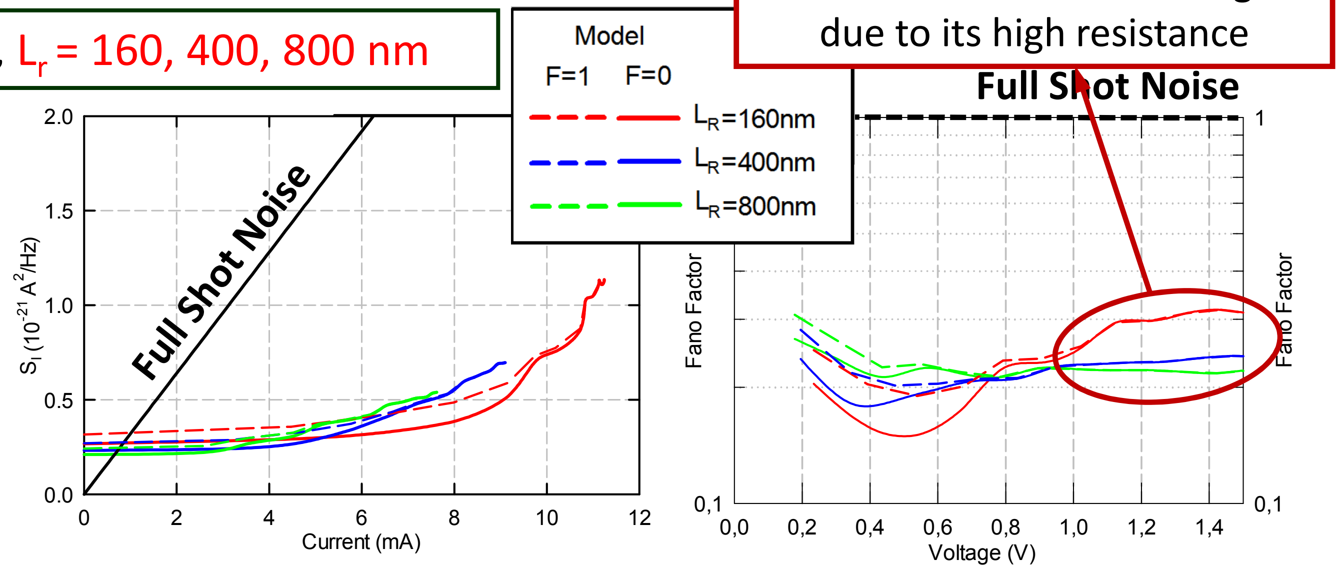
Completely suppressed shot noise in the active region F=0



Noise at high bias depend just on the noise of the drain region due to its high resistance

L_s = 200 nm, L_d = 550 nm, L_r = 160, 400, 800 nm

Noise in the active region (and therefore the signature of full/suppressed shot noise) is only visible on the total noise at intermediate voltages



Conclusions

- Measurements of noise performed in a set of recessed planar InGaAs/InAlAs diodes with different dimensions show potential signs of shot noise suppression in the structures due to the presence of a potential barrier

- A detailed analysis of the noise contribution of the different regions of the devices shows that contact, source and drain resistances strongly affect the value of the total noise

- The possible shot noise suppression appearing under the recess could just be visible on the total noise at intermediate bias (before the onset of intervalley scattering) where the resistance of the drain region is still low

- Devices with reduced access and drain resistances should be fabricated in order to obtain conclusive results