Physics-based Noise Simulation of Semiconductor Devices Under Large-signal Operation

Original
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EDS Mini-Colloquium On

Advanced Electron Devices modelling and Technology

Friday 1st May 2009. Admission is free

University College Dublin, Ireland

(Engineering Building (no 49 on the campus map)

Sponsored by

IEEE Electron Devices Society, IEEE UKRI (AP/ED/Photonics/MTT) Societies Joint Chapter

09:15 – 09:50 Registration

09:50 – 10:00 Welcome Remarks: Prof Tom Brazil, University College Dublin

10:00 Opening Remarks: Prof Ali A Rezazadeh, Chair IEEE UKRI (AP/ED/Photonics/MTT) Societies Joint Chapter, University of Manchester, UK.

10:10 IEEE EDS Activities: Prof J J Liu (Central University of Florida, USA)

10:30 – 12:45 SESSION I

Chair: Prof. Giovanni Ghione

10:30 – 11:15: Roadmap for 22 nm and Beyond, Prof Hiroshi Iwai (Tokyo Institute of Technology, Yokohama, Japan

11-15 – 12:00: Small- and Large-Signal Modelling of GaAs- and GaN-based Transistors Prof Tom Brazil (University City Dublin, Ireland)

12:00 – 12:45: Advanced electrostatic discharge (ESD) protection solutions in BiCMOS/CMOS technologies, Prof J J Liu (University of Central Florida, USA)

12:45 – 2:00: **Lunch Break**

02:00 – 02:30: PhD Research Students Poster Session

02:30 – 04:20: SESSION II

Chair: Prof Tom Brazil

02:30 – 03:15: Physics-based Noise Simulation of Semiconductor Devices Under Large-signal Operation, Prof Giovanni Ghione, Fabrizio Bonani and Simona Donati Guerrieri (Politecnico di Torino,Italy)

03-15 – 04:00: Passive 3D multilayer microwave components for development of compact multifunctional MMICs, Prof Ali A. Rezazadeh (University of Manchester, UK)

04:00 – 04:20: Closing Remarks: Prof Hiroshi Iwai (Tokyo Institute of Technology, Japan)

For further information, please contact Prof. Tom Brazil, +353-1-716 1929, tom.brazil@ucd.ie

Physics-based Noise Simulation of Semiconductor Devices Under Large-signal Operation

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Outline

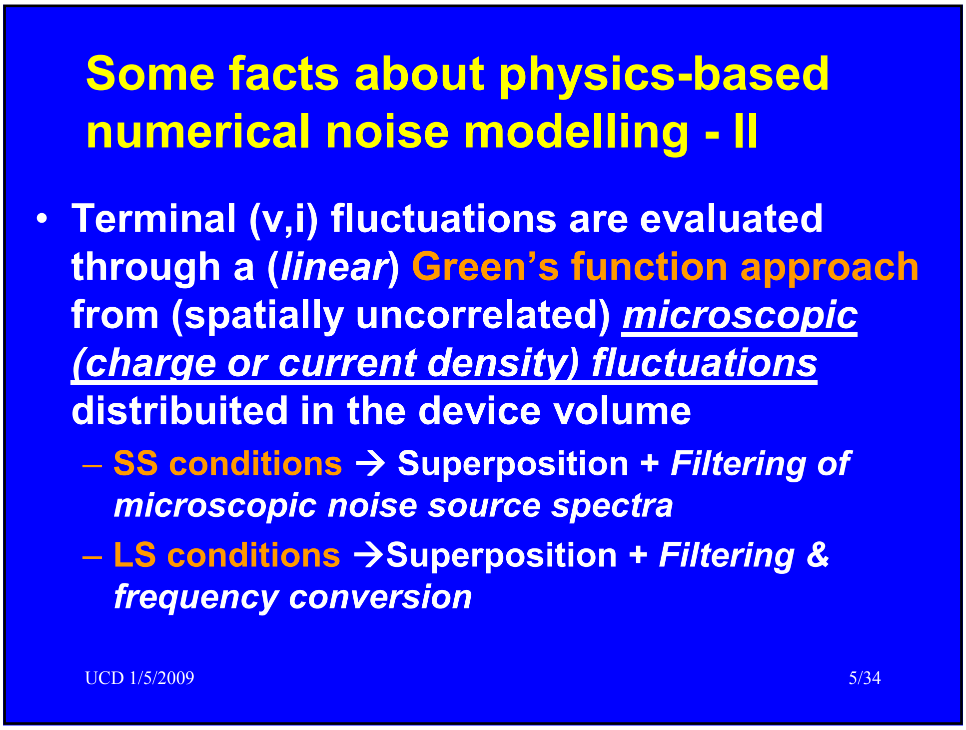
- **Motivation**
- **Overview on numerical noise modelling**
  - **Small-signal (stationary)**
  - ***Forced* large-signal (cyclostationary)**
  - ***Autonomous* large signal**
- **Modeling low frequency noise**
- **Evaluating the Large Signal working point**
- **Case studies**
- **Conclusions**

Motivation

- Low-noise circuits important in RF & microwave telecommunication systems
  - Linear circuits (e.g., low noise amplifiers)
  - "Nonlinear" circuits (e.g., mixers, frequency multipliers, oscillators)
- Physics-based simulation is a powerful tool for:
  - TCAD Device design and optimization
  - Development of compact, circuit-oriented model with sound physical basis
  - Understanding exotic noise mechanisms (1/f?)

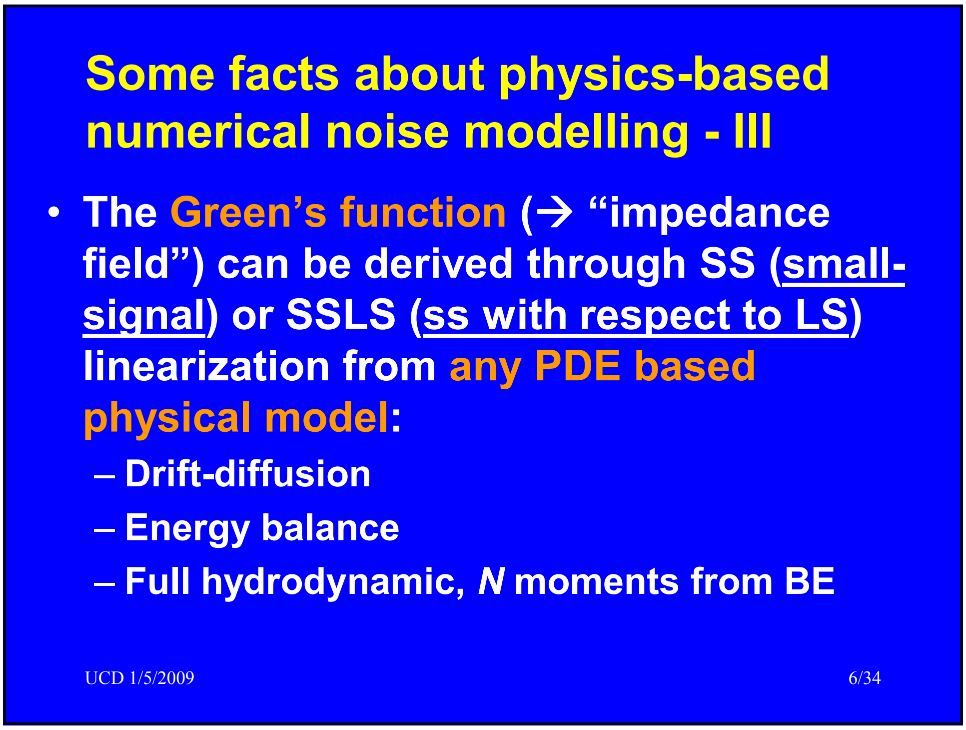
Some facts about physics-based numerical noise modelling - I

- Microscopic (carrier velocity or population) fluctuations are a *small perturbation* of
  - DC steady-state → *Small-signal, stationary noise*
  - Large-signal (quasi) - periodic steady state → *LS (quasi)-cyclostationary noise*
  - LS steady-state of autonomous system → *LS (oscillator) stationary (?) noise*



Some facts about physics-based numerical noise modelling - II

- Terminal (v,i) fluctuations are evaluated through a (*linear*) Green’s function approach from (spatially uncorrelated) *microscopic (charge or current density) fluctuations* distribuited in the device volume
  - SS conditions → Superposition + *Filtering of microscopic noise source spectra*
  - LS conditions →Superposition + *Filtering & frequency conversion*



Some facts about physics-based numerical noise modelling - III

- The Green’s function (→ “impedance field”) can be derived through SS (small-signal) or SSLS (ss with respect to LS) linearization from any PDE based physical model:
  - Drift-diffusion
  - Energy balance
  - Full hydrodynamic, *N* moments from BE

Summary of simulation steps

1. Evaluate the **noiseless working point**
    - Noise sources are **switched off**
    - Solution is (φ_0, n_0,p_0,$n_{t,k0}$)
    - The working point depends on the applied generators → **might depend on time and require mixed-mode simulation → CPU-intensive for the large-signal case**
2. Add (model) the **microscopic noise sources**
    - The working point is perturbed by **fluctuations $\delta\alpha$**
3. Solve the (linear) perturbed system to evaluate the **terminal electrical fluctuations** (noise generators) through the Green's function approach

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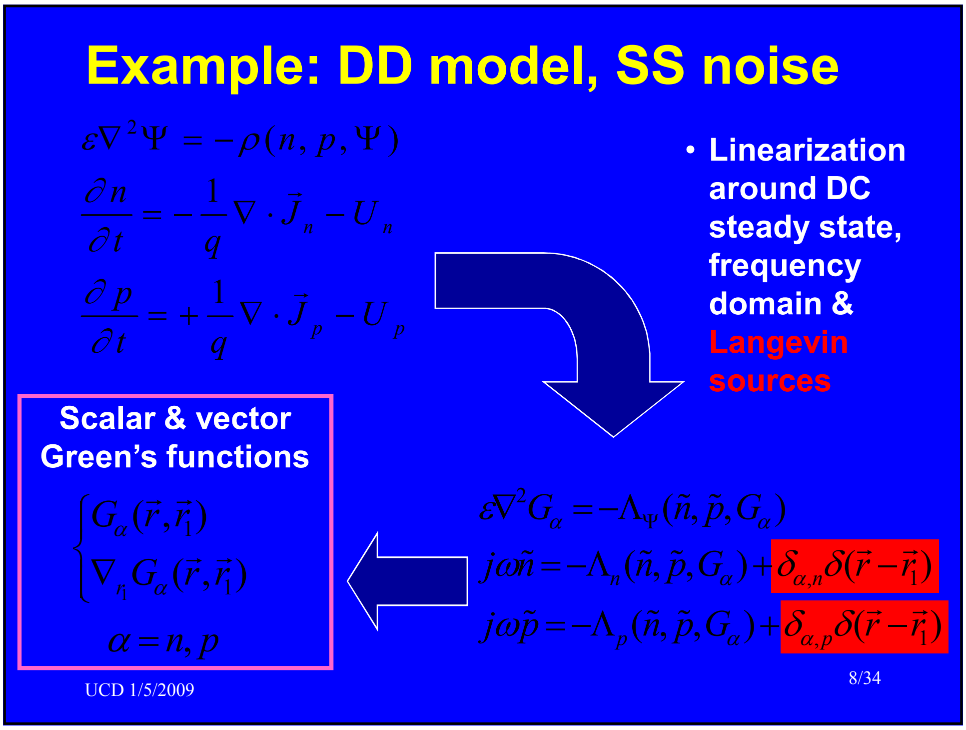
Example: DD model, SS noise



$$\varepsilon\nabla^2\Psi = -\rho(n,p,\Psi)$$

$$\frac{\partial n}{\partial t} = -\frac{1}{q}\nabla\cdot\vec{J}_n - U_n$$

$$\frac{\partial p}{\partial t} = +\frac{1}{q}\nabla\cdot\vec{J}_p - U_p$$

- Linearization around DC steady state, frequency domain & **Langevin sources**

$$\varepsilon\nabla^2 G_\alpha = -\Lambda_\Psi(\tilde{n},\tilde{p},G_\alpha)$$

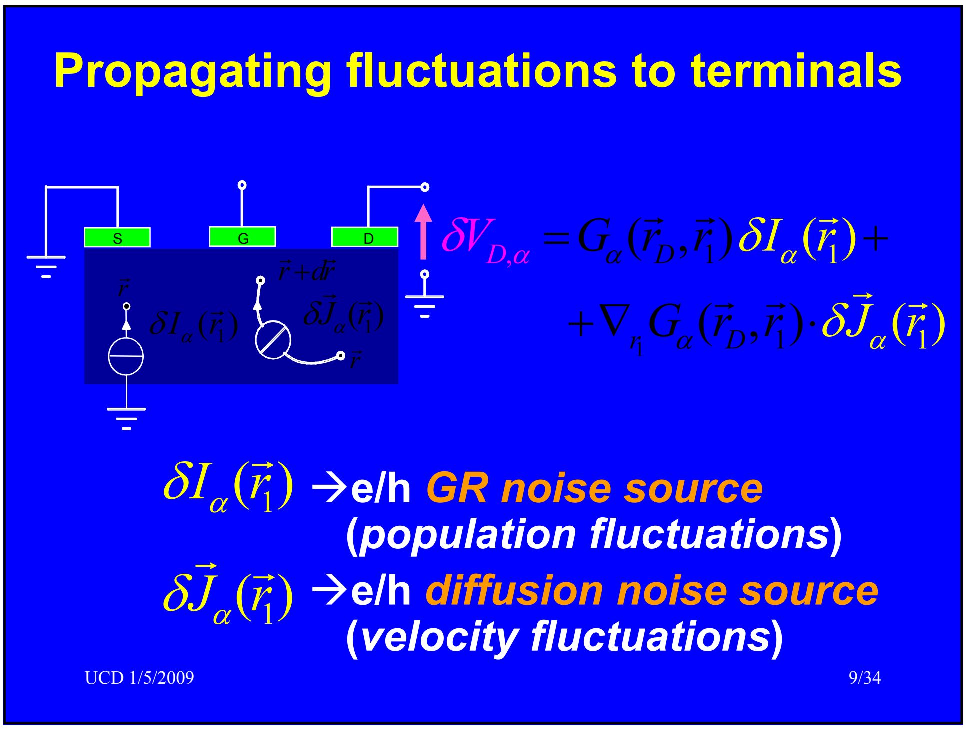
$$j\omega\tilde{n} = -\Lambda_n(\tilde{n},\tilde{p},G_\alpha) + \boxed{\delta_{\alpha,n}\delta(\vec{r}-\vec{r}_1)}$$

$$j\omega\tilde{p} = -\Lambda_p(\tilde{n},\tilde{p},G_\alpha) + \boxed{\delta_{\alpha,p}\delta(\vec{r}-\vec{r}_1)}$$

Scalar & vector Green's functions

$$\begin{cases} G_\alpha(\vec{r},\vec{r}_1) \\ \nabla_{r_1} G_\alpha(\vec{r},\vec{r}_1) \end{cases}$$

$$\alpha = n, p$$



Propagating fluctuations to terminals

$$\delta V_{D,\alpha} = G_\alpha(\vec{r}_D,\vec{r}_1)\,\delta I_\alpha(\vec{r}_1) + \\ +\nabla_{\vec{r}_1} G_\alpha(\vec{r}_D,\vec{r}_1)\cdot \delta\vec{J}_\alpha(\vec{r}_1)$$

$\delta I_\alpha(\vec{r}_1)$ →e/h *GR noise source* (*population fluctuations*)

$\delta \vec{J}_\alpha(\vec{r}_1)$ →e/h *diffusion noise source* (*velocity fluctuations*)

SS noise power spectra

- Correlation matrix of open-circuit voltage noise fluctuations:

$$S_{\delta V_i \delta V_j}(\omega) = \sum_{\alpha=n,p}\int_{\Omega} \vec{G}_\alpha(\vec{r}_i,\vec{r},\omega)\cdot \mathbf{K}_{\delta\vec{J}_\alpha\delta\vec{J}_\alpha}(\vec{r},\omega)\cdot \vec{G}^*_\alpha(\vec{r}_j,\vec{r},\omega)\,d\vec{r} + \\ + \sum_{\alpha,\beta=n,p}\int_{\Omega} G_\alpha(\vec{r}_i,\vec{r},\omega)\,K_{\gamma_\alpha\gamma_\beta}(\vec{r},\omega)\,G^*_\beta(\vec{r}_j,\vec{r},\omega)\,d\vec{r}$$

$\mathbf{K}_{\delta\vec{J}_\alpha\delta\vec{J}_\alpha} = 4q^2\alpha\mathbf{D}_\alpha$ →e/h *diffusion* *local noise source*

$K_{\gamma_\alpha\gamma_\beta}(\vec{r},\omega)$ →e/h *GR* *local noise source*

LS cyclostationary noise - I

- Analog applications often require periodic or quasi-periodic LS operation
- In LS operation microscopic noise sources are amplitude modulated by the periodic LS steady-state leading to → cyclostationary microscopic sources with correlated frequency components
- Those are described by the Sideband Correlation Matrix (SCM) formalism

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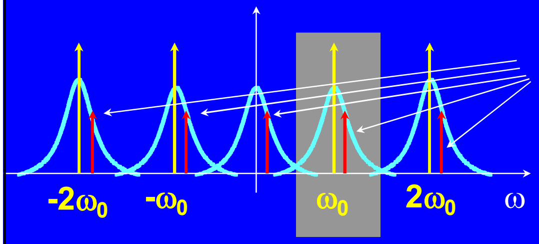
Cyclostationary noise formalism

- Only the spectral components in each sideband having the same distance from the LS harmonics, are correlated



Correlated sidebands of noise process *y*

$\omega_k = k\omega_0$ **LS harmonics**

$\omega_k^+ = \omega_k + \omega$ ***sidebands***

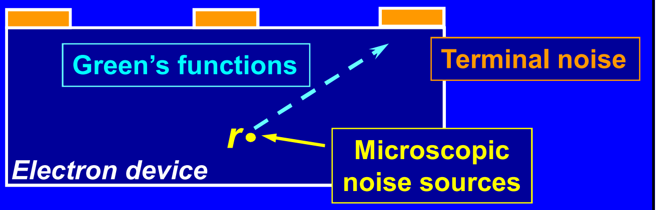
- 2nd order statistical properties through the ***sideband correlation matrix*** ***(SCM):***

$$\boxed{\left(\mathbf{S}_{y,y}(\omega)\right)_{k,l} = \left\langle \tilde{y}\left(\omega_k^+\right) \tilde{y}^*\left(\omega_l^+\right) \right\rangle}$$

ω **is called *sideband frequency***

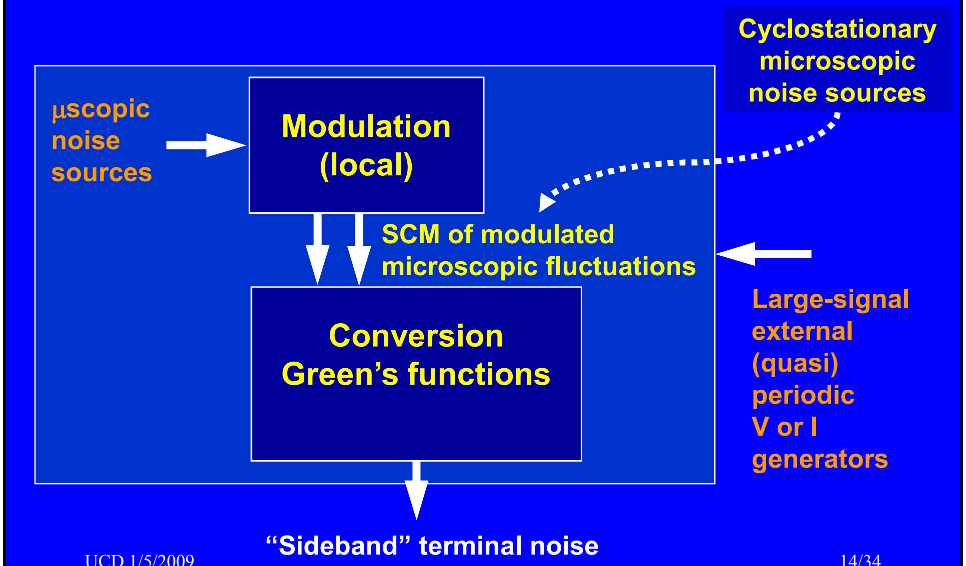
LS cyclostationary noise - II

LS extension of Green's function approach



- Green's functions → conversion Green's functions, implying noise frequency conversion into LS spectrum sidebands
- After propagation & conversion noise around each harmonic is from
  - microscopic noise source at that sideband
  - source conversion from other sidebands

LS cyclostationary noise - III



Noise in autonomous systems

- Oscillator noise → object of investigation and debate at circuit and system level
- Alper Demir's approach (system level) accounting both for coloured and white noise sources → viable way for extension to device level
- Work by group of Seoul National University (white diffusion noise sources)

Numerical implementation

- Through standard (e.g. finite box – Scharfetter-Gummel) discretization the Green's function is derived from a linear system (← SS or SSLS)
- Efficient evaluation of the Green's functions at device terminals through adjoint and generalized adjoint techniques
- ☹ Bottleneck: LS (quasi) periodic solution through Harmonic Balance

Low frequency noise modelling

- Low-frequency (coloured, 1/f or Lorentzian) noise important in many analog applications (mixers, multipliers, oscillators…) where noise frequency conversion takes place
- Low-frequency noise → superposition of bulk, surface or interface GR noise
- GR trap-assisted noise → theory developed by van Vliet in 1960 → trap level rate equations added to DD model

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Model + traps: bipolar drift-diffusion

- N_t traps included
- Device mesh: N_i internal nodes and N_x external nodes on metallic contacts
- Device contacts: N_c+1, one grounded

$$\nabla^2\varphi = -\frac{q}{\varepsilon}\left(p - n - \sum_{k=1}^{N} n_{t,k}\right)$$

$$\frac{\partial n}{\partial t} = -\nabla\cdot\left(n\mu_n\nabla\varphi - D_n\nabla n\right) - U_n + \gamma_n$$

$$\frac{\partial p}{\partial t} = +\nabla\cdot\left(p\mu_p\nabla\varphi + D_p\nabla p\right) - U_p + \gamma_p$$

$$\boxed{\frac{\partial n_{t,k}}{\partial t} = -U_k + \gamma_k \qquad k = 1,\ldots,N}$$

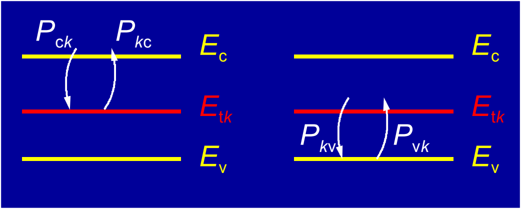
Trap level transition rates

- *N* (local) trap rate equations → SRH model
- **Noninteracting traps** considered; superposition → **1/f spectrum**

total trap density c=(cross sect.) x v_{th}

$$P_{\mathrm{c}k} = c_{n,k} n (N_{\mathrm{t},k} - n_{\mathrm{t},k}), \qquad P_{k\mathrm{c}} = c_{n,k} n_{1,k} n_{\mathrm{t},k},$$

$$P_{\mathrm{v}k} = c_{p,k} p_{1,k} (N_{\mathrm{t},k} - n_{\mathrm{t},k}), \qquad P_{k\mathrm{v}} = c_{p,k} p n_{\mathrm{t},k}$$



$$n_{1,k} = N_{\mathrm{c}} \exp\left(\frac{E_{\mathrm{t},k} - E_{\mathrm{c}}}{k_{\mathrm{B}} T}\right)$$

$$p_{1,k} = N_{\mathrm{v}} \exp\left(\frac{E_{\mathrm{v}} - E_{\mathrm{t},k}}{k_{\mathrm{B}} T}\right)$$

SS - RG local noise source

$$K_{\gamma_n,\gamma_n} = 2\left(P_{\mathrm{c}k0} + P_{k\mathrm{c}0}\right),$$

$$K_{\gamma_p,\gamma_p} = 2\left(P_{\mathrm{v}k0} + P_{k\mathrm{v}0}\right),$$

$$K_{\gamma_n,\gamma_p} = 0,$$

$$K_{\gamma_k,\gamma_k} = 2\left(P_{\mathrm{c}k0} + P_{k\mathrm{c}0} + P_{\mathrm{v}k0} + P_{k\mathrm{v}0}\right),$$

$$K_{\gamma_n,\gamma_k} = -2\left(P_{\mathrm{c}k0} + P_{k\mathrm{c}0}\right),$$

$$K_{\gamma_p,\gamma_k} = 2\left(P_{\mathrm{v}k0} + P_{k\mathrm{v}0}\right)$$

γ_n → Langevin source, e-continuity equation

γ_p → Langevin source, p-continuity equation

γ_k → Langevin source, *k*th trap rate equation

Trap transition probabilities

$$P_{\mathrm{c}k} = c_{n,k} n (N_{\mathrm{t},k} - n_{\mathrm{t},k}),$$

$$P_{k\mathrm{c}} = c_{n,k} n_{1,k} n_{\mathrm{t},k},$$

$$P_{\mathrm{v}k} = c_{p,k} p_{1,k} (N_{\mathrm{t},k} - n_{\mathrm{t},k}),$$

$$P_{k\mathrm{v}} = c_{p,k} p n_{\mathrm{t},k}$$

LS - RG local noise source SCM

- In LS conditions the white microscopic RG noise sources are (quasi) periodically modulated by the working point
- Noise source SCM, e.g.:

$$\left(\mathbf{K}_{\gamma_n,\gamma_n}\right)_{l,m} = 2\left(P_{ck0,l-m} + P_{kc0,l-m}\right)$$

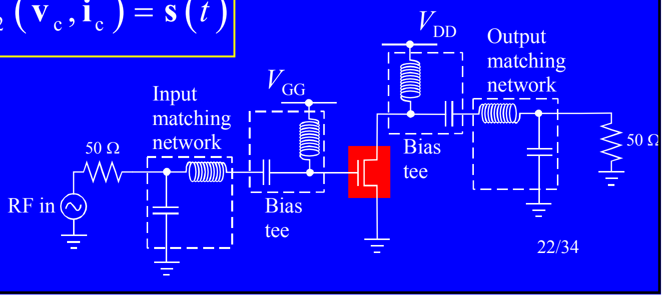
…..etc.

(*l*-*m*)-th Fourier component of transition rate

Solving the PB model in LS: the embedding circuit

- Represented, in its simplest form, by a memory relationship between v_c, i_c and the applied generators s(*t*)
  - For periodic excitation, s(*t*+*T*)=s(*t*)
  - For autonomous circuit, s(*t*)=0

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{e}_1\left(\mathbf{v}_c,\mathbf{i}_c\right) + \mathbf{e}_2\left(\mathbf{v}_c,\mathbf{i}_c\right) = \mathbf{s}\left(t\right)}$$



Solving the PB model in LS: total discretized model & solution

- (Space) discretized PB model + embedding circuit → differential algebraic equation (DAE)

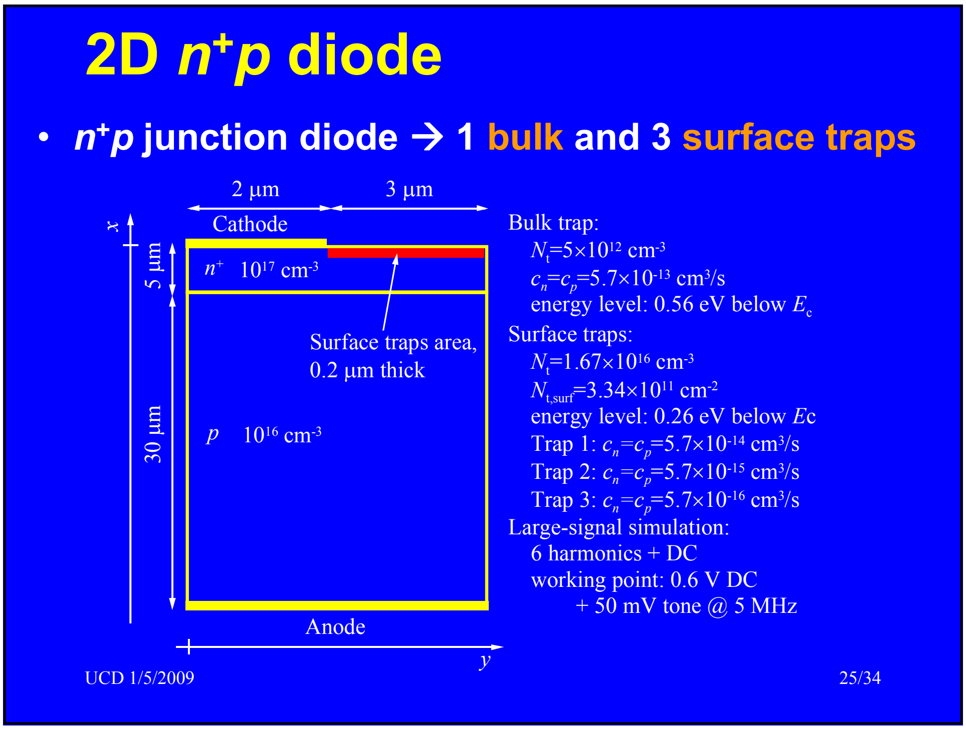
System size: $\boxed{N_{\mathrm{eq}} = (3+N_{\mathrm{t}})(N_{\mathrm{i}}+N_{\mathrm{x}})+2N_{\mathrm{c}}}$

For a 3-terminal device with 2000 nodes mesh and 3 traps N_{eq}=12,004!

- Direct computation of the steady-state response
  - Frequency-domain: Harmonic Balance (HB)
  - Time-domain: shooting method
  - Autonomous case?

Case studies

- 2D n^+p diode
  - motivation: low-frequency noise compact modelling usually based on amplitude modulation of stationary SS noise generators → is this generally correct / accurate?
- GaAs MESFET and AlGaAs/GaAs HEMT Mixer
  - 2D LS mixed-mode noise simulation



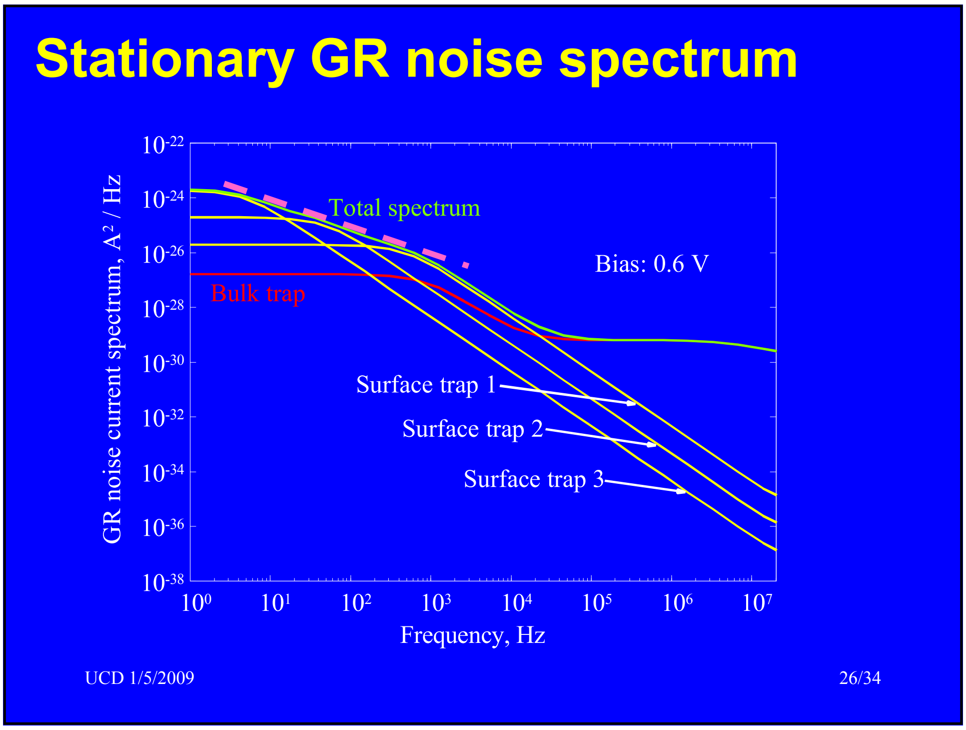
2D n^+p diode

- n^+p junction diode → 1 bulk and 3 surface traps

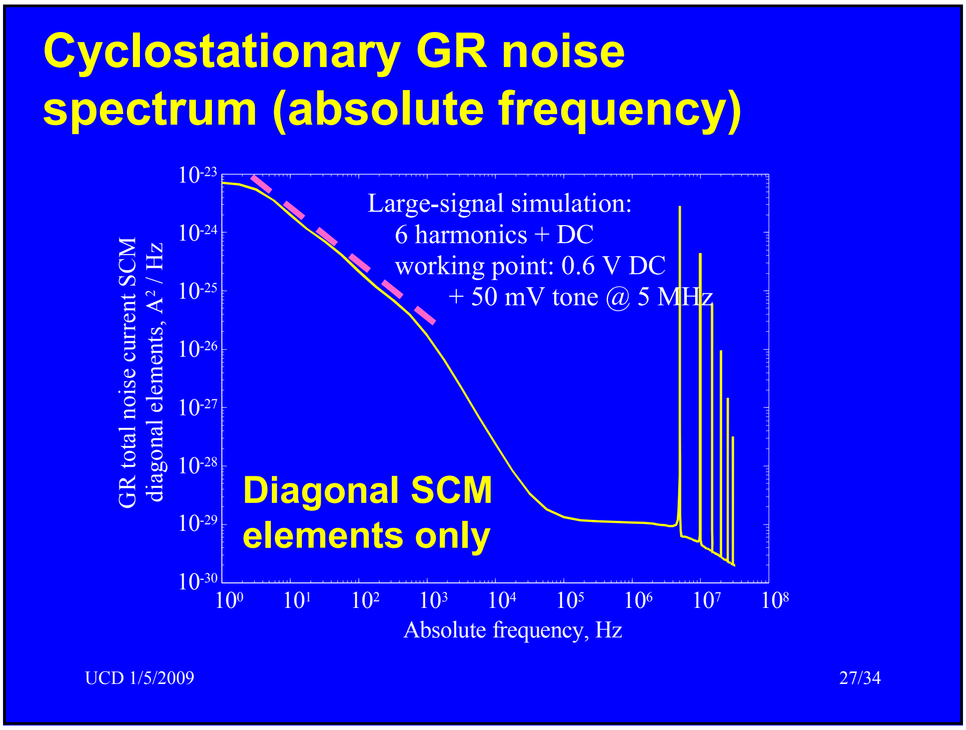
Bulk trap:
N_t=5×10^{12} cm^{-3}
c_n=c_p=5.7×10^{-13} cm^3/s
energy level: 0.56 eV below E_c

Surface traps:
N_t=1.67×10^{16} cm^{-3}
$N_{t,surf}$=3.34×10^{11} cm^{-2}
energy level: 0.26 eV below E_c
Trap 1: c_n=c_p=5.7×10^{-14} cm^3/s
Trap 2: c_n=c_p=5.7×10^{-15} cm^3/s
Trap 3: c_n=c_p=5.7×10^{-16} cm^3/s

Large-signal simulation:
6 harmonics + DC
working point: 0.6 V DC
+ 50 mV tone @ 5 MHz



Stationary GR noise spectrum



Cyclostationary GR noise spectrum (absolute frequency)

Large-signal simulation:
6 harmonics + DC
working point: 0.6 V DC
+ 50 mV tone @ 5 MHz

Diagonal SCM elements only

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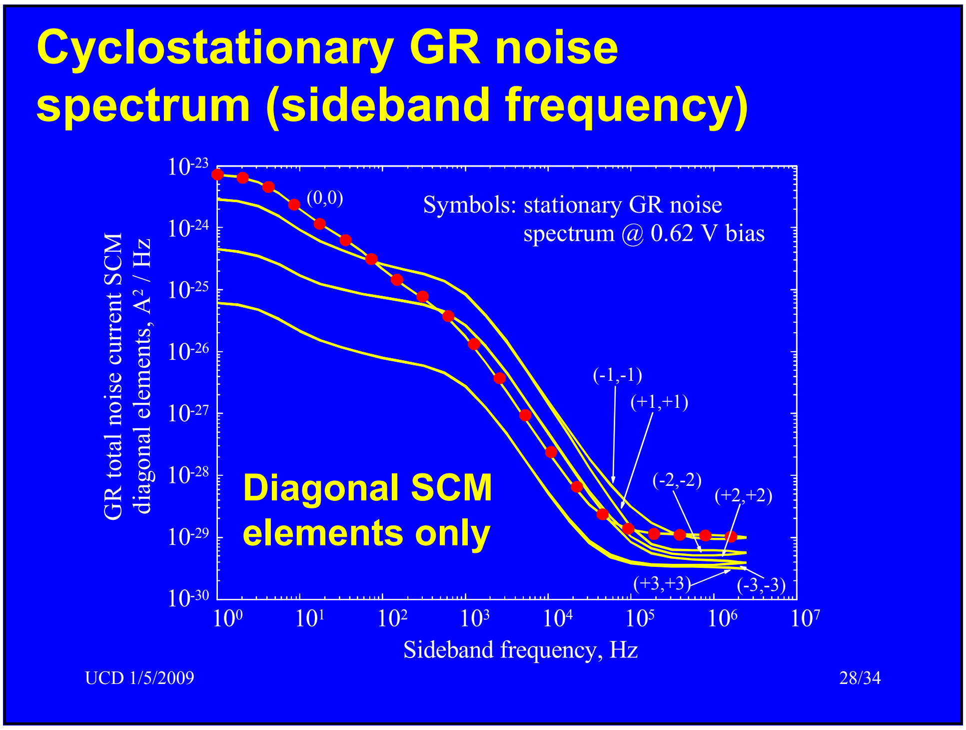

Cyclostationary GR noise spectrum (sideband frequency)

Symbols: stationary GR noise
spectrum @ 0.62 V bias

Diagonal SCM elements only

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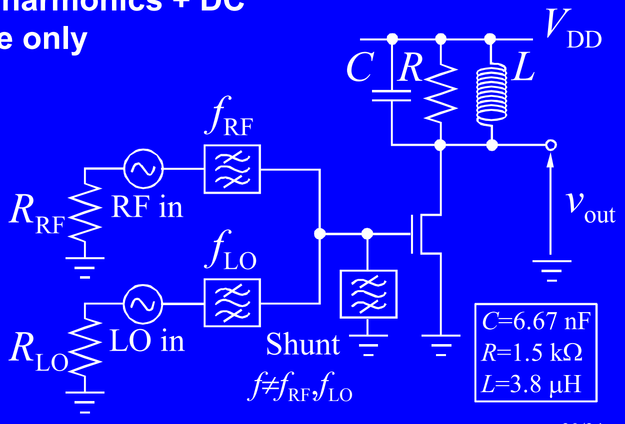
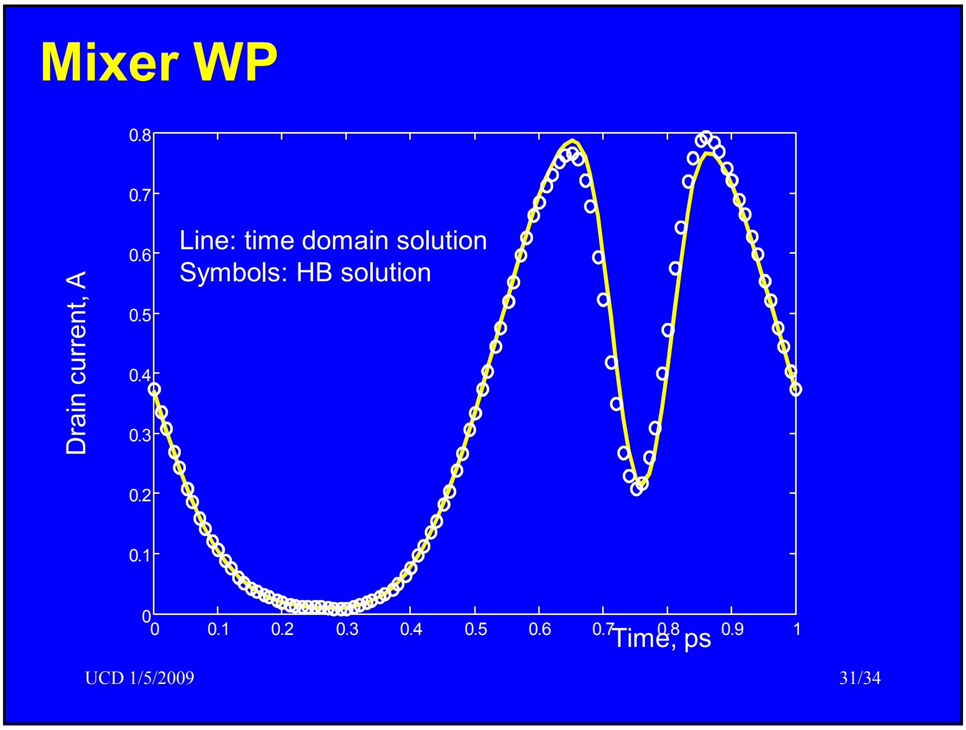
Remarks

- The SS 1/f like behaviour is preserved in the (0,0) sideband
- However, conversion to upper sidebands acts differently for bulk and surface traps
- Therefore, noise in upper sidebands is markedly different from modulated SS noise → which would have the same 1/f like behaviour for all sidebands
- Impact on compact modelling!

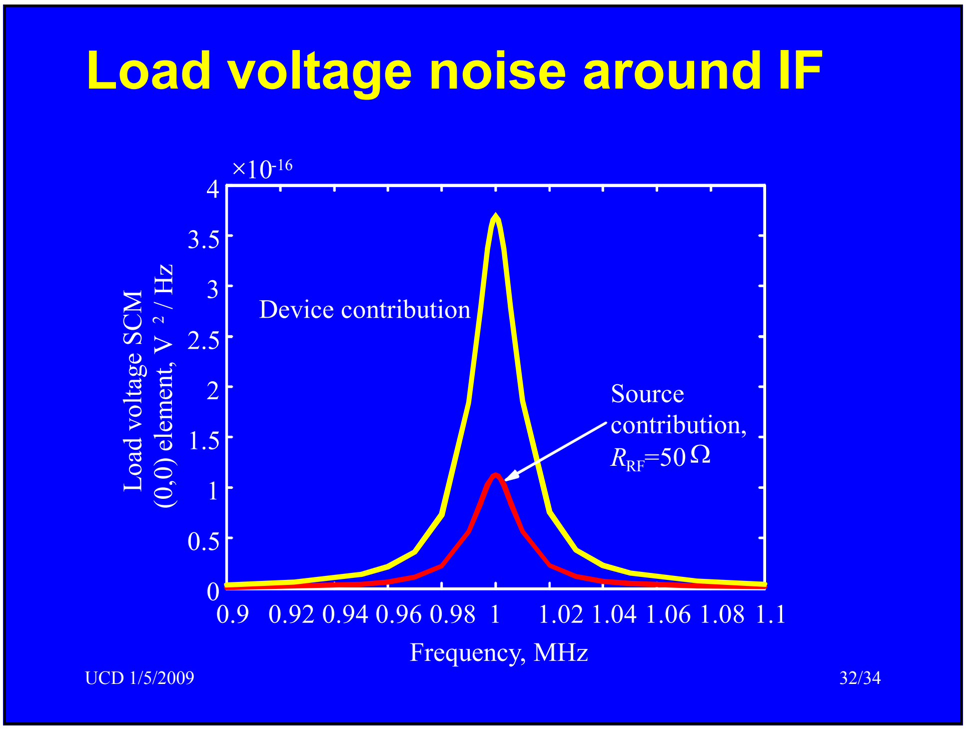
Mixer circuit

- Downconversion mixer, f_{LO}=1 GHz, f_{RF}=1.001 GHz
- Noiseless LO
- Device: 0.3 µm gate HEMT, 100 µm gate periphery
- 1300 nodes, 4 harmonics + DC
- Diffusion noise only



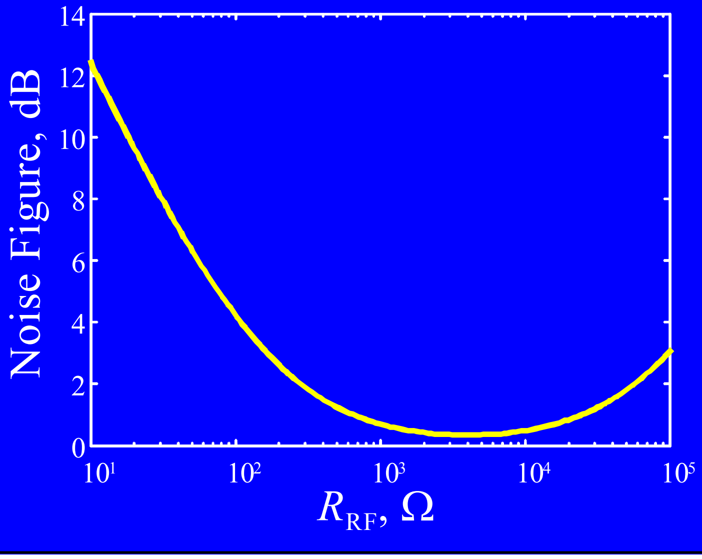


Mixer WP



Load voltage noise around IF

Intrinsic noise figure vs. RF source resistance



Conclusions

- Numerical noise simulation has (hopefully) reached maturity
- Progress made in understanding low-frequency noise (→1/f) and its frequency conversion (also → compact modelling)
- Incouraging advances in oscillator PB modelling
- LS noise simulation requires more efficient WP solvers (time domain?)
- General strategy for LS compact modelling still an open problem – but this is another story!