• Notes Set 12: Physics and Noise of Resonant tunnel diodes

- this is a very long and very detailed treatement of a very specialized device
- mostly hobby horse interest.

This leaves us with only a few devices left to model:

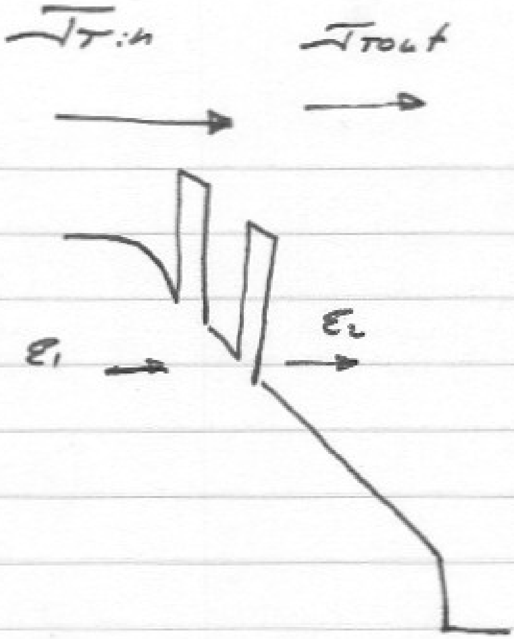
<u>optical devices</u> Lasers, photodiodes, avalanche photodiodes.

<u>Mixers</u> (really a circuit problem)

<u>2-terminal negative-resistance devices.</u>
Impatts, Gunns, RTDs.

We will defer the optical devices until we consider <u>optical</u> <u>communication</u>, & the mixers until we consider <u>heterodyne</u> receivers. 2-terminal negative-resistance devices are generally hard to model for noise, As the process involve either avalanche multiplication or intervalley scattering with negative differential mobility. We will have to analyze noise in the avalanche photodiode — but later...

Will now analyze RTD (resonant-tunnel-diode) noise for no reason other than it being of hobby interest. Mudakkar Reddy is developing very fast RTDs that potentially have low noise.



Analyze quantum well region

Flux into well

$$J_{Tin} = G_1 \mathcal{E}_1$$

stored charge in well

$$\rho_g \cong \tau_g \cdot J_{Tout}$$

Flux out of well

$$J_{Tout} = J_{Tin} + j\omega\rho_g$$

$$= J_{Tin} + j\omega\tau_g J_{Tout}$$

$$J_{Tout} = \frac{J_{Tin}}{1 + j\omega\tau_g} = \frac{G_1 \mathcal{E}_1}{1 + j\omega\tau_g}.$$

// we will add noise to the model later by adding shot noise fluctuations to the tunnelling current into the well

/// This assumes that all tunnelling events into the well are statistically independent.

There will be a dc tunnelling current flux into the well, and through the device, of J_{dc}. From this, the ac small signal tunnelling current into the well will be:

$$J_{Tin} = G_1 E_1 + J_n$$

J_n = noise current; $\frac{d}{df}\langle J_n J_n^* \rangle = 2q J_n$.

... we will add the noise current later

Note also

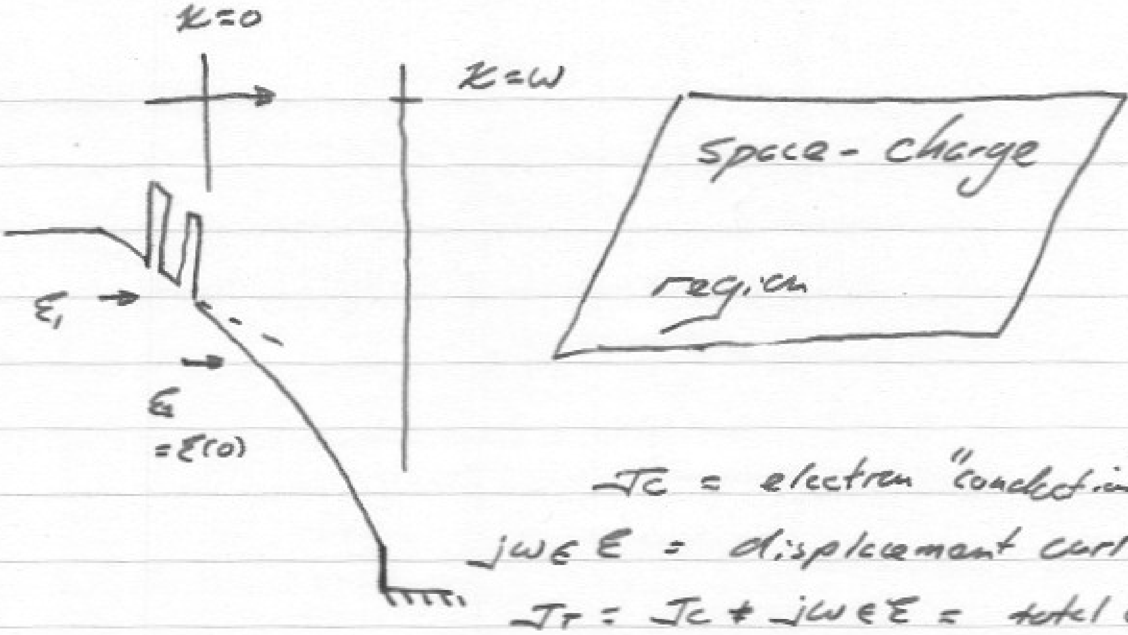
$$\mathcal{E}_2 = \mathcal{E}_1 + \frac{\rho_q}{\epsilon} = \mathcal{E}_1 + \frac{\tau_q J_{tout}}{\epsilon}$$

$$= \mathcal{E}_1 + \frac{(\tau_q G_1/\epsilon)\,\mathcal{E}_1}{1 + j\omega\tau_q}$$

$$= \frac{\mathcal{E}_1 + j\omega\tau_q\mathcal{E}_1 + (\tau_q G_1/\epsilon)\mathcal{E}_1}{1 + j\omega\tau_q}$$

$$\mathcal{E}_2 = \mathcal{E}_1(1 + \tau_q \cdot G_1/\epsilon)\,\frac{1 + j\omega\tau_q/(1 + \tau_q G_1/\epsilon)}{1 + j\omega\tau_q}$$

This is real and significant in high-performance RTD's. $G_1 = \frac{\partial J_{qw}}{\partial \mathcal{E}_{qw}}$, and hence $\frac{1}{\epsilon} G_1 = \frac{1}{\epsilon}\frac{\partial J_T}{\partial \mathcal{E}}$ is akin to an "RC" time constant of the quantum well, while τ_q is its charge storage time. In RTD's with thin barriers, $\tau_q G_1/\epsilon \sim O(1)$. The term $(1 + \tau_q G_1/\epsilon)$ represents screening of the AC field by the charge in the well.



J_C = electron "conduction" current

$j\omega\epsilon E$ = displacement current

$J_T = J_C + j\omega\epsilon E$ = total current

at $x=0$

$$J_C = \frac{G_1 \mathcal{E}_1}{1 + j\omega\tau_g}$$

$$= \frac{G_1 \mathcal{E}_1}{1 + j\omega\tau_g} \cdot \frac{\mathcal{E}_2}{\mathcal{E}_1} \cdot \frac{(1 + j\omega\tau_g)}{(1 + \tau_g \cdot G_1/\epsilon)\left(1 + j\omega\tau_g/(1 + \tau_g G_1/\epsilon)\right)}$$

$$J_C = \left(\frac{G_1}{1 + \tau_g G_1/\epsilon}\right) \cdot \frac{\mathcal{E}_2}{1 + j\omega\tau_g/(1 + \tau_g G_1/\epsilon)}$$

$$\boxed{J_C = G_{ex} \cdot \frac{\mathcal{E}_2}{1 + j\omega\tau_\epsilon}}$$

where $G_{ex} = \dfrac{G_1}{1 + \tau_g G_1/\epsilon}$, $\tau_\epsilon = \dfrac{\tau_g}{1 + \tau_g G_1/\epsilon}$

Total Current

$$J_T = J_C(x) + j\omega\epsilon\,\mathcal{E}(x) = \text{constant}$$

with position!

$$J_T(0) = \left[\left(\frac{G_{ex}}{1+j\omega\tau_e}\right) + j\omega\epsilon\right]\underbrace{\mathcal{E}(0)}_{=\,\mathcal{E}_2}$$

AC small signal quantities throughout...

Charge moves through drift region at velocity v_s.

$$\Rightarrow J_c(x) = J_c(0)\,e^{-j\omega x/v_s}$$

Voltage drop across device

$$V(\omega) = \int_0^W \mathcal{E}(x)\,dx$$

but $\dfrac{d\mathcal{E}}{dx} = \dfrac{J_c}{\epsilon\, v_s}$

sol:

$$\mathcal{E}(x) = \mathcal{E}(0) + \int_0^x \frac{J_c(x)}{\epsilon v_s} \cdot dx$$

$$= \mathcal{E}(0) + \frac{1}{\epsilon v_{sat}} \int_0^x J_c(0)\, e^{-j\omega x / v_{sat}}\, dx$$

$$\cong \mathcal{E}(0) + \frac{1}{\epsilon v_{sat}} \int_0^x J_c(0) \left[1 - j\omega x / v_{sat}\right] dx$$

$$= \mathcal{E}(0) + \frac{J_c(0)}{\epsilon v_{sat}} \left[x - j\omega x^2 / 2 v_s \right]$$

—

Again, ~~[illegible]~~ $V(\omega) = \int_0^W \mathcal{E}(x)\, dx$

$$V(\omega) = \mathcal{E}_z \cdot W + \frac{J_c(0)}{\epsilon v_{sat}} \cdot \left[\frac{W^2}{2} - \frac{j\omega W^3}{6 v_{sat}} \right]$$

$$= \mathcal{E}_z \cdot W + \frac{J_c(0)}{\epsilon} \frac{W^2}{2 v_{sat}} \left[1 - \frac{j\omega W}{3 v_{sat}} \right]$$

Side note:

We obtained $\mathcal{E}(x)$ by integration. This was unnecessary. We could also have used continuity of the total (conduction + displacement) current.

$$\tilde{J}_T = J_c(x) + j\omega\epsilon\,\mathcal{E}(x); \quad J_T(x_1) = J_T(x_2)$$

for all x_1, x_2.

so: $J_c(0) + j\omega\epsilon\,\mathcal{E}(0) - J_c(x) = j\omega\epsilon\,\mathcal{E}(x)$

$$J_c(0)\left[1 - e^{-j\omega x/v_s}\right] + j\omega\epsilon\,\mathcal{E}(0) = j\omega\epsilon\,\mathcal{E}(x)$$

$$\mathcal{E}(x) = \frac{J_c(0)}{j\omega\epsilon}\left[1 - e^{-j\omega x/v}\right] + \mathcal{E}(0)$$

$$\cong \frac{J_c(0)}{j\omega\epsilon}\left[\frac{j\omega x}{v} - \frac{(j\omega)^2 x^2}{2v^2}\right] + \mathcal{E}(0)$$

$$= \frac{J_c(0)}{\epsilon v}\left[x - \frac{j\omega x^2}{2v_s}\right] + \mathcal{E}(0)$$

which is the same answer...

$$v(\omega) = \mathcal{E}_z \cdot W + \frac{J_c(0)}{\epsilon} \cdot \frac{W^2}{3\, v_{sat}} \cdot \frac{3}{2} \left[1 - j\omega \frac{W}{3\, v_{sat}} \right]$$

$$V(\omega) = \mathcal{E}_z \cdot W + \frac{J_c(0) \cdot (3/2)\, W \tau_T}{\epsilon} \left[1 - j\omega \tau_t \right]$$

$$\boxed{\text{where} \quad \tau_t = W / 3\, v_{sat}}$$

but $J_c = G_{ex}\, \mathcal{E}_z / (1 + j\omega \tau_t)$

so:

$$V(\omega) = \mathcal{E}_z \cdot W + \frac{G_{ex} \cdot \mathcal{E}_z}{1 + j\omega\tau_t} \cdot \frac{3}{2} \frac{\tau_t}{\epsilon} \cdot W \left[1 - j\omega \tau_t \right]$$

$$\frac{V}{\mathcal{E}_z} = W \left[1 + \frac{3}{2} (G_{ex}/\epsilon)\, \tau_T \, \frac{1 - j\omega\tau_t}{1 + j\omega\tau_t} \right]$$

The device admittance is:

$$Y = \frac{J_T}{V} = \frac{E_2}{V} \cdot \frac{J_T}{E_2}$$

$$= \frac{G_{ex}/(1 + j\omega\tau_E) + j\omega\epsilon}{W\left[1 + \frac{G_{ex}}{\epsilon} \cdot \tau_T \cdot \frac{3}{2}\,\frac{1 - j\omega\tau_E}{1 + j\omega\tau_E}\right]}$$

$$= \frac{(G_{ex}/W)/(1 + j\omega\tau_E) + j\omega\epsilon/W}{1 + \frac{G_{ex}}{\epsilon}\,\tau_{Tr} \cdot \frac{3}{2}\,\frac{1 - j\omega\tau_E}{1 + j\omega\tau_E}}$$

$$=$$

$$Y = \frac{(G_{ex}/\omega) + j\omega\frac{\epsilon}{\omega}(1 + j\omega\tau_\epsilon)}{1 + j\omega\tau_\epsilon + [3G_{ex}\tau_t/2\epsilon](1 - j\omega\tau_t)}$$

$$= \frac{(G_{ex}/\omega) + j\omega\frac{\epsilon}{\omega}(1 + j\omega\tau_\epsilon)}{1 + (3G_{ex}\tau_t/2\epsilon) + j\omega[\tau_\epsilon - \tau_t(3G_{ex}\tau_t/2\epsilon)]}$$

$$= \frac{(G_{ex}/\omega) + j\omega\frac{\epsilon}{\omega}(1 + j\omega\tau_\epsilon)}{[1 + 3G_{ex}\tau_t/2\epsilon]\left[1 + \frac{j\omega(\tau_\epsilon - \tau_t\cdot(3G_{ex}\tau_t/2\epsilon))}{1 + 3G_{ex}\tau_t/2\epsilon}\right]}$$

At this point I have to simplify

use $(1 + j\omega\tau_1)(1 + j\omega\tau_2) \cong 1 + j\omega(\tau_1 + \tau_2)$

$$\frac{(1 + j\omega\tau_1)}{1 + j\omega\tau_2} \cong 1 + j\omega(\tau_1 - \tau_2) \quad , \text{etc.}$$

$$Y = \frac{G_{ex}}{\omega} \frac{1}{1 + 3G_{ex}\tau_t/2\epsilon} \frac{1}{1 + j\omega\left[\dfrac{\tau_\epsilon - \tau_t(3G_{ex}\tau_0/2\epsilon)}{1 + 3G_{ex}\tau_t/2\epsilon}\right]}$$

$$+ j\omega \frac{(\epsilon/\omega)}{1 + 3G_{ex}\tau_t/2\epsilon} \frac{1}{1 + j\omega \cdot \dfrac{3G_{ex}\tau_t/2\epsilon}{1 + 3G_{ex}\tau_t/2\epsilon}(-\tau_\epsilon + \tau_b)}$$

[now write $\tau_{sc} = \tau_t \cdot 3/2 = w/2v_{sct}$]

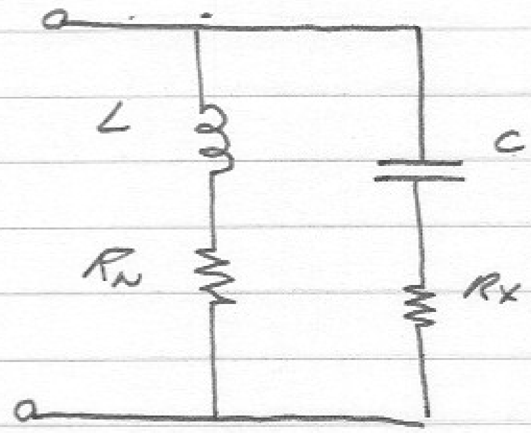
$$Y = \frac{G_{ex}}{\omega} \; \frac{1}{1 + G_{ex}\tau_{sc}/\epsilon} \; \frac{1}{1 + j\omega\left[\dfrac{\tau_\epsilon - (2/3)\tau_{sc}\,(\tau_{sc} G_{ex}/\epsilon)}{1 + G_{ex}\tau_{sc}/\epsilon}\right]}$$

$$+ j\omega \cdot \left(\frac{\epsilon}{\omega}\right) \frac{1}{1 + G_{ex}\tau_{sc}/\epsilon} \; \frac{1}{1 - j\omega\,(\tau_\epsilon + (2/3)\tau_{sc}\,(G_{ex}\tau_{sc}/\epsilon))}$$

where $G_{ex} = \dfrac{G_1}{1 + G_1 \tau_g/\epsilon}$ & $\tau_\epsilon = \dfrac{\tau_g}{1 + \tau_g G_1/\epsilon}$

This allows us to construct an equivalent circuit model of the RTD...

note that G_{ex} & G_1 are <u>negative</u> in the negative differential resistance region.



$$R_W^{-1} = \frac{1}{W} \cdot \frac{G_{ex}}{1 + G_{ex}\tau_{sc}/\epsilon} \quad \text{where} \quad G_{ex} = \frac{G_1}{1 + G_1 \tau_g/\epsilon}$$

L = quantum well inductance

$$: \quad L/R_W = \frac{\tau_\epsilon - (2/3)\tau_{sc}(\tau_{sc} G_{ex}/\epsilon)}{1 + G_{ex}\tau_{sc}/\epsilon}$$

negative in NDR region

C = depl. layer capacitance

R_X .... probably negligible..

Noise:

$$I_{cin} = G_1 \mathcal{E}_1 + \delta I_t \qquad \text{shot noise}$$

$$I_{cout} = \frac{G_1 \mathcal{E}_1 + \delta I_t}{1 + j\omega \tau_g}$$

$$\mathcal{E}_2 = \mathcal{E}_1 + (\tau_g / \epsilon) I_{cout}$$

$$= \mathcal{E}_1 + (\tau_g / \epsilon) \; I_c(0)$$

In the s.c. region:

$$\frac{d\mathcal{E}}{dx} = \frac{J_c}{\epsilon\, v_{sct}} \cdot e^{-j\omega x / v_s}$$

so:

$$\mathcal{E}(x) = \mathcal{E}_2 + \frac{J_c(0)}{\epsilon\, v_{sct}} \left[x - j\omega x^2 / 2 v_{sct} \right]$$

and

$$V = \mathcal{E}_2 \cdot W + \frac{J_c(0)}{\epsilon} W \frac{W}{2 v_{sct}} \left[1 - j\omega \frac{W}{3 v_{sct}} \right]$$

$$V = \mathcal{E}_2 \cdot W + \frac{J_c(0)}{\epsilon} W \tau_{sc} \left[1 - j\omega (2/3) \tau_{sc} \right]$$

to compute the short-circuit noise current we set $v = 0$.

$$J_c(0) = \frac{-\mathcal{E}_2 \cdot \epsilon}{\tau_{sc} \left(1 - j\omega (2/3) \tau_{sc} \right)}$$

while $J_T = J_c(0) + j\omega \epsilon \mathcal{E}_2$

$$-J_c(0)\cdot\frac{\tau_{sc}}{\epsilon}\cdot\left(1-j\omega(2/3)\,\tau_{sc}\right) = \mathcal{E}_2$$

so

$$-J_c(0)\,\frac{\tau_{sc}}{\epsilon}\left[1-j\omega(2/3\;\tau_{sc})\right] = \mathcal{E}_1 + \frac{\tau_g}{\epsilon}\,J_c(0)$$

hence

$$-\mathcal{E}_1 = J_c(0)\left[\frac{\tau_{sc}}{\epsilon}\left(1-j\omega\,\frac{2\tau_{sc}}{3}\right) + \frac{\tau_g}{\epsilon}\right]$$

but we also have:

$$J_c(0) = \frac{G_1\,\mathcal{E}_1}{1+j\omega\tau_g} + \frac{\delta J_t}{1+j\omega\tau_g}$$

so

$$J_c(0)\,(1 + j\omega\tau_g) = G_1 E_1 + \delta J_t$$

so

$$G_1 E_1 = J_c(0)\,(1 + j\omega\tau_g) - \delta J_t$$

<u>combine to get:</u>

$$\delta J_t - J_c(0)\,(1 + j\omega\tau_g) = G_1 J_c(0) \cdot \left[\frac{\tau_g}{\epsilon} + \frac{\tau_{sc}}{\epsilon} \left(1 \bullet j\omega \frac{2\tau_{sc}}{3} \right) \right]$$

$$\left(\frac{J_c(\omega)}{\delta J_T}\right)^{-1} = 1 + j\omega\tau_g + \frac{G_1\tau_g}{\epsilon} + \frac{G_1\tau_{sc}}{\epsilon}$$

$$+ \; j\omega\left(\frac{2}{3}\right)\frac{G_1\tau_{sc}}{\epsilon}\cdot\tau_{sc}$$

$$= 1 + (G_1/\epsilon)(\tau_g + \tau_{sc})$$

$$+ \; j\omega\tau_g - j\omega\left(\frac{2\tau_{sc}}{3}\right)\frac{G_1\tau_{sc}}{\epsilon}$$

$$= \left[1 + (G_1/\epsilon)(\tau_g + \tau_{sc})\right]$$

$$\cdot\left[1 + j\omega\left(\frac{\tau_g - (2\tau_{sc}/3)\,G_1\tau_{sc}/\epsilon}{1 + (G_1/\epsilon)(\tau_g + \tau_{sc})}\right)\right]$$

Multiply by areas to get currents. Then the short circuit noise current spectral density is:

$$\frac{d}{df}\langle I_n I_n^* \rangle$$

$$= \frac{2q\, I_{dc}}{\left(1 + \frac{G_1}{\epsilon}\left(\tau_{sc} + \tau_g\right)\right)^2 \left(1 + \omega^2 \left(\frac{\tau_g - (2\tau_{sc}/3)\, G_1 \tau_{sc}/\epsilon}{1 + (G_1/\epsilon)(\tau_g + \tau_{sc})}\right)^2\right)}$$

note that in the negative differential resistance region, G_1 is negative, and the noise current is larger than <u>shot</u> <u>noise</u>.

... similar comments apply to $\dfrac{\tau_g - (2\tau_{sc}/3)\, G_1 \tau_{sc}/\epsilon}{1 + (G_1/\epsilon)(\tau_g + \tau_{sc})}$

I have now spent too much time on RTD noise, and so will guess without proof some relationships without carrying through the math. Specifically, the time constant written in terms of τ_e & τ_{sc} for the $Y(\omega)$ characteristics should be the same as the time constant given in terms of τ_g & τ_{sc} for the noise characteristics.

specifically, If the well has a net conductance

$$G_1 = \frac{\partial J}{\partial \mathcal{E}}$$

Then the RTD net conductance is

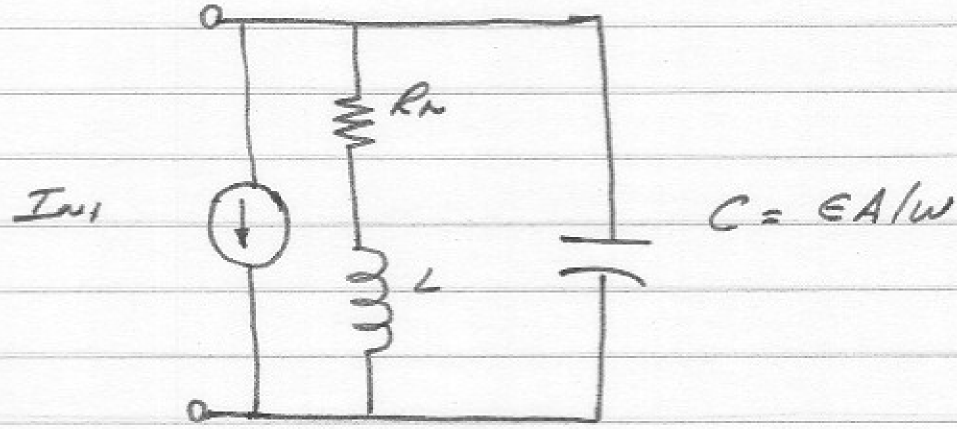
$$G_{net} = \frac{G_1}{1 + \frac{G_1}{\epsilon}(\tau_{sc} + \tau_g)} \cdot \frac{1}{w}$$

This is simply a voltage divider formula between the well conductance G_1 & the space-charge resistance.

$\tau_{sc} \cdot W / \epsilon$ & $\tau_g \cdot w / \epsilon$.

Alternatively, compare the well conductance time constant $\epsilon / G_1 = \left[\frac{\partial J}{\partial \mathcal{E}}\right]^{-1} \epsilon$ to the transit times...

RTO model:



$$G_N = \frac{1}{R_N} = \frac{A}{w} \cdot \left.\frac{\partial J}{\partial E}\right|_{\text{well}} \cdot \frac{1}{1 + \frac{1}{\epsilon}\frac{\partial J}{\partial E}(\tau_{sc} + \tau_g)}$$

area.

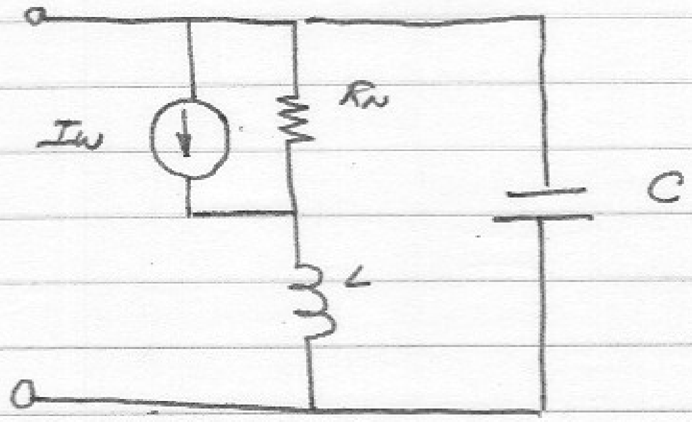
$$\frac{\partial J}{\partial E} = G_1$$

$$L := \tau / G = \frac{1}{G} \cdot \left[\frac{\tau_g - (2\tau_{sc}/3)\, G_1 \tau_{sc}/\epsilon}{1 + (G_1/\epsilon)(\tau_{sc} + \tau_g)} \right]$$

spectral density of I_{N1} given above

both G_N & L are negative in the N. D. R. region

We can model more clearly like so:

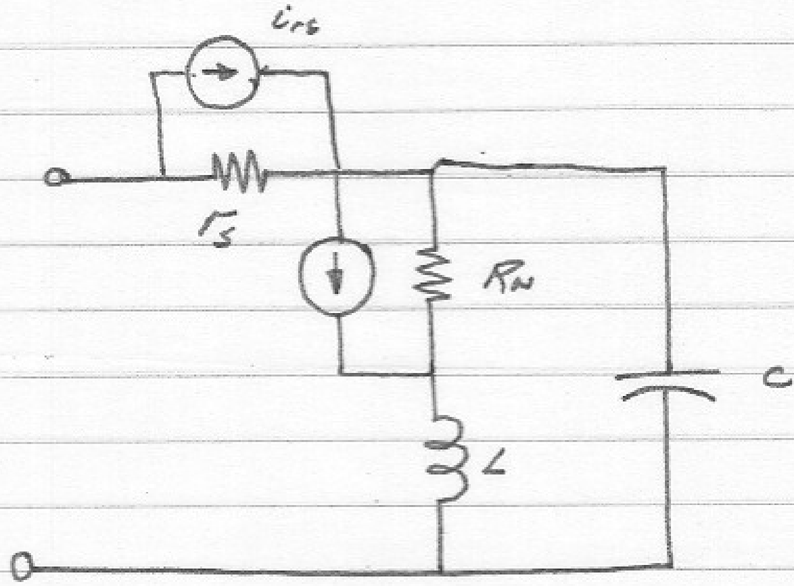


here: I_w has a spectral density:

$$\frac{\partial}{\partial f}\langle I_n I_n^*\rangle = 2q\, I_{dc} \cdot \left[\frac{1}{1 + \frac{G_1}{\epsilon}(\tau_{sc} + \tau_g)}\right]^2$$

$> 2q\, I_{dc}$ in the N.D.R. region.

We must also add a parasitic series resistance and its noise:



$\frac{d}{df}\langle i_{rs}\, i_{rs}^* \rangle = 4kT/r_s$, other parameters given earlier.

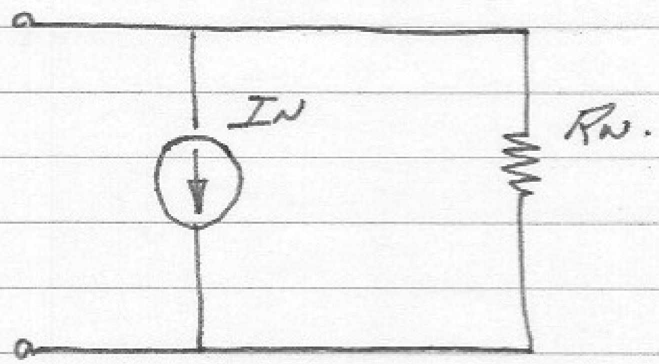
Note RTDs have a negative resistance cutoff frequency f_{max}:

$$f_{max} \cong \begin{cases} \dfrac{1}{2\pi \sqrt{|R_N|/R_s}\; C} & \text{if } \sqrt{R_N R_s}\, C \gg \tau_g + \tau_{sc} \\[2ex] \cong \dfrac{1}{2\pi} \dfrac{1}{\sqrt[4]{R_N C}} \dfrac{1}{\sqrt[4]{R_S C}} \dfrac{1}{\sqrt[2]{\tau_g}} & \text{if } \sqrt{R_N R_s}\, C \gg \tau_g + \tau_{sc} \end{cases}$$

and $\tau_g \gg \tau_{sc}$.

I will not attempt a frequency-dependent noise analysis here. Lets restrict ourselves to $f \ll f_{max}$ and $r_s \ll |R_N|$.

Then our device model is



$$(R_N)^{-1} = \frac{A}{W} \overbrace{\left.\frac{\partial J}{\partial E}\right|_{well}}^{G_1} \frac{1}{1 + \frac{1}{\epsilon} \left.\frac{\partial J}{\partial E}\right|_w (\tau_{sc} + \tau_g)} = G_N$$

I_N: $$S_{I_N I_N}(f) = \frac{2q\, I_{dc}}{\left[1 + \frac{1}{\epsilon} \left.\frac{\partial J}{\partial E}\right|_w (\tau_{sc} + \tau_g)\right]^2}$$

we can write:

$$S_{I_N I_N}(f) = 4k\, T_{eq} \cdot |G_N|$$

from which:

$$T_{eq} = \frac{2q\, J_{dc} \cdot W}{\left[1 + \frac{1}{\epsilon} \frac{\partial J}{\partial E}\Big|_W (\tau_{sc} + \tau_g) \right]} \quad \frac{1}{\frac{\partial J}{\partial E}\Big|_W}$$

... we see immediately that the RTD space-charge layer thickness W should be as small as possible consistent with obtaining sufficient f_{max}.

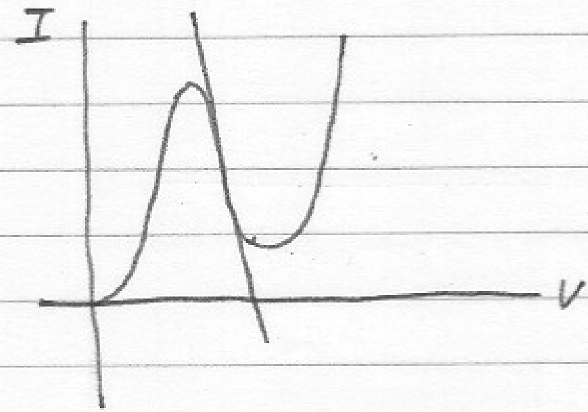
This point is new. Esaki diodes have 10:1 to 100:1 thinner space-charge layers than do typical RTDs. RTD's are much noisier. Madhekar needs to clean up this analysis & publish it!.

We note that the term

$$1 + \frac{1}{\epsilon} \left.\frac{\partial I}{\partial E}\right|_{\omega} (\tau_{sc} + \tau_{g})$$ is not observable.

Since we can measure G_N from the DC I-V

curve:



... we want to write in terms of this

parameter

$$G_N = \frac{G_1/\omega}{1 + \frac{G_1}{\epsilon}(\tau_{sc} + \tau_{g})}$$

From which:

$$G_1 = \frac{W G_N}{1 - \frac{W G_N}{\epsilon} \cdot (\tau_{sc} + \tau_g)}$$

note the difference in units:

$$G_N \triangleq \left.\frac{\partial J}{\partial V}\right|_{device} \quad ; \quad G_1 \triangleq \left.\frac{\partial J}{\partial E}\right|_{well}$$

$$G_1 = \frac{W \cdot G_N}{1 - \frac{G_N}{C} (\tau_{sc} + \tau_g)}$$

here G_N is the externally observable negative conductance & C the capacitance.

writing: $\tau_{RC} \triangleq R_N C$,

negative in the N.D.R. region,

$$G_1 = \frac{W G_N}{1 - (\tau_{sc} + \tau_g)/\tau_{RC}}$$

$$|G_1| \left\{ \begin{array}{ll} > |G_N| & \text{positive-resistance region} \\ < |G_N| & \text{negative resistance region.} \end{array} \right.$$

Now

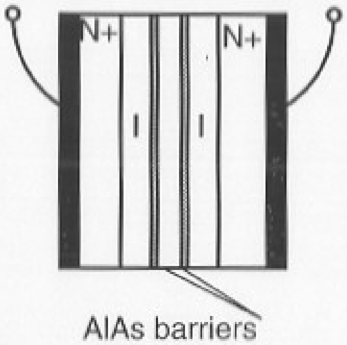
$$\left[\frac{1}{1 + \frac{G_1}{\epsilon}(\tau_{sc} + \tau_g)} \right] = 1 - (\tau_{sc} + \tau_g)/\tau_{RC}$$

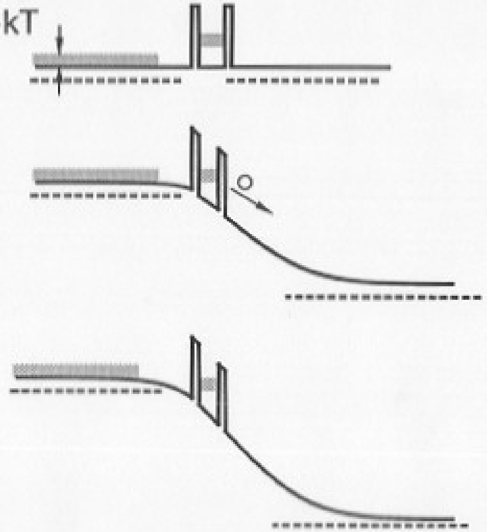
and

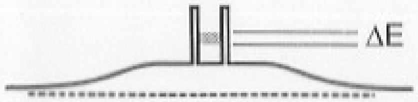
$$\frac{G_1}{1 + \frac{G_1}{\epsilon}(\tau_{sc} + \tau_g)} = W G_N \quad !$$

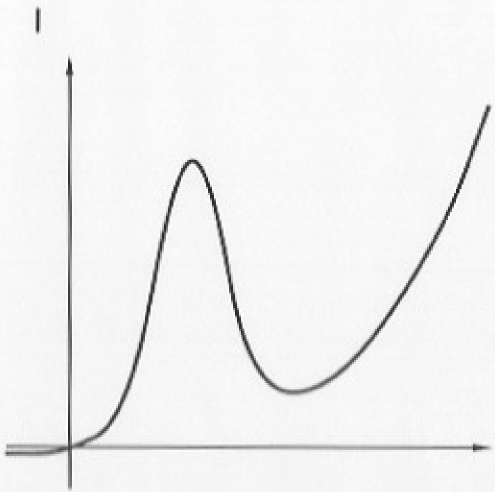
Resonant Tunneling Diodes

(Sollner, MIT Lincoln Labs)
(Esaki)





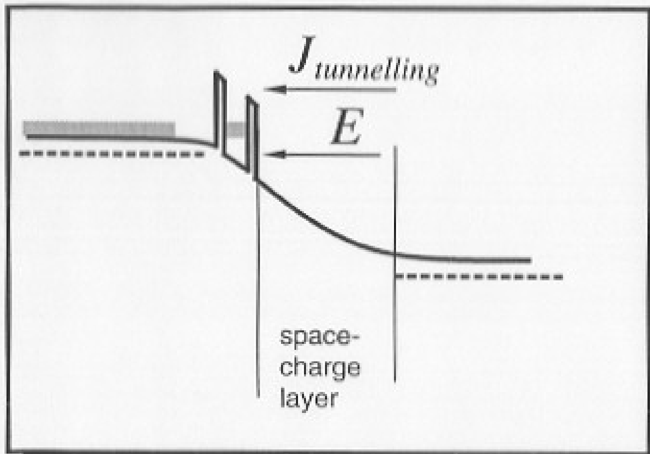


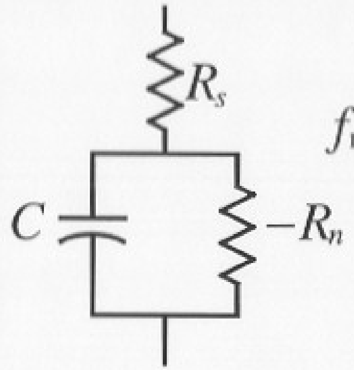


Strong current flow when electron reservoir and confined state are aligned in energy.

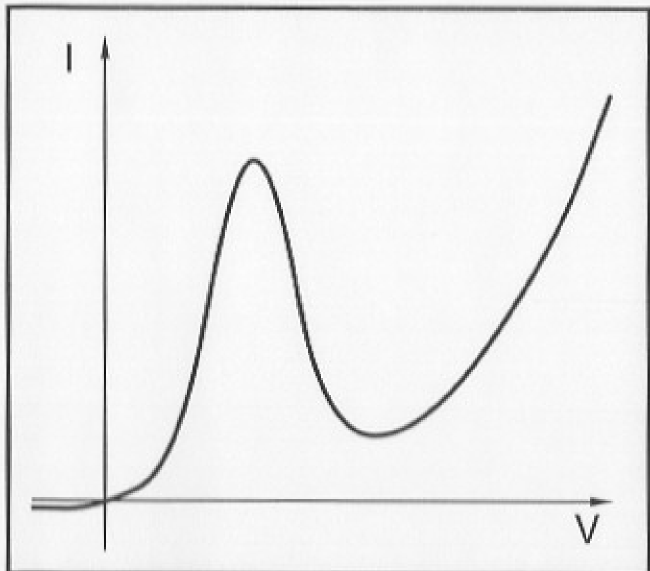
Narrower AlAs barriers decrease the electron trapping time, increasing ΔE, and increasing the peak current density. Increasing the emitter doping increases the electron supply and therefore also increases the current density.

Parameters Determining RTD Fmax





$$f_{\max} = \frac{1}{2\pi R_n C}\sqrt{\frac{R_n - R_s}{R_s}}$$

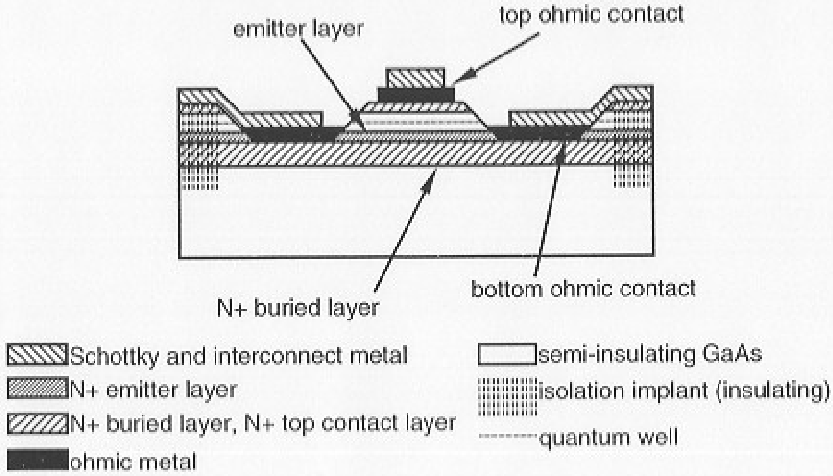


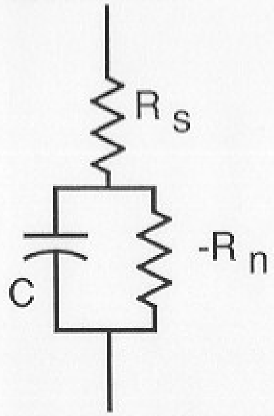
$$\frac{1}{R_n C} = \frac{1}{\varepsilon}\frac{dJ}{dE}$$

-Maximized by designing for high current density (reliability limits)

-R_S then limits f_{max}:
InAs/AlSb RTD's have very low (10^{-7} Ω-cm^2) contact resistance, & have attained f_{max}=1.3 THz.

RTDs as negative-resistance oscillators





Coupled to the conjugate impedance -jX(ω), the RTD will oscillate if R(ω) <0

$$Z(\omega) = R_s + \frac{-R_n}{1 - j\omega R_n C}$$

$$= R(\omega) + jX(\omega)$$

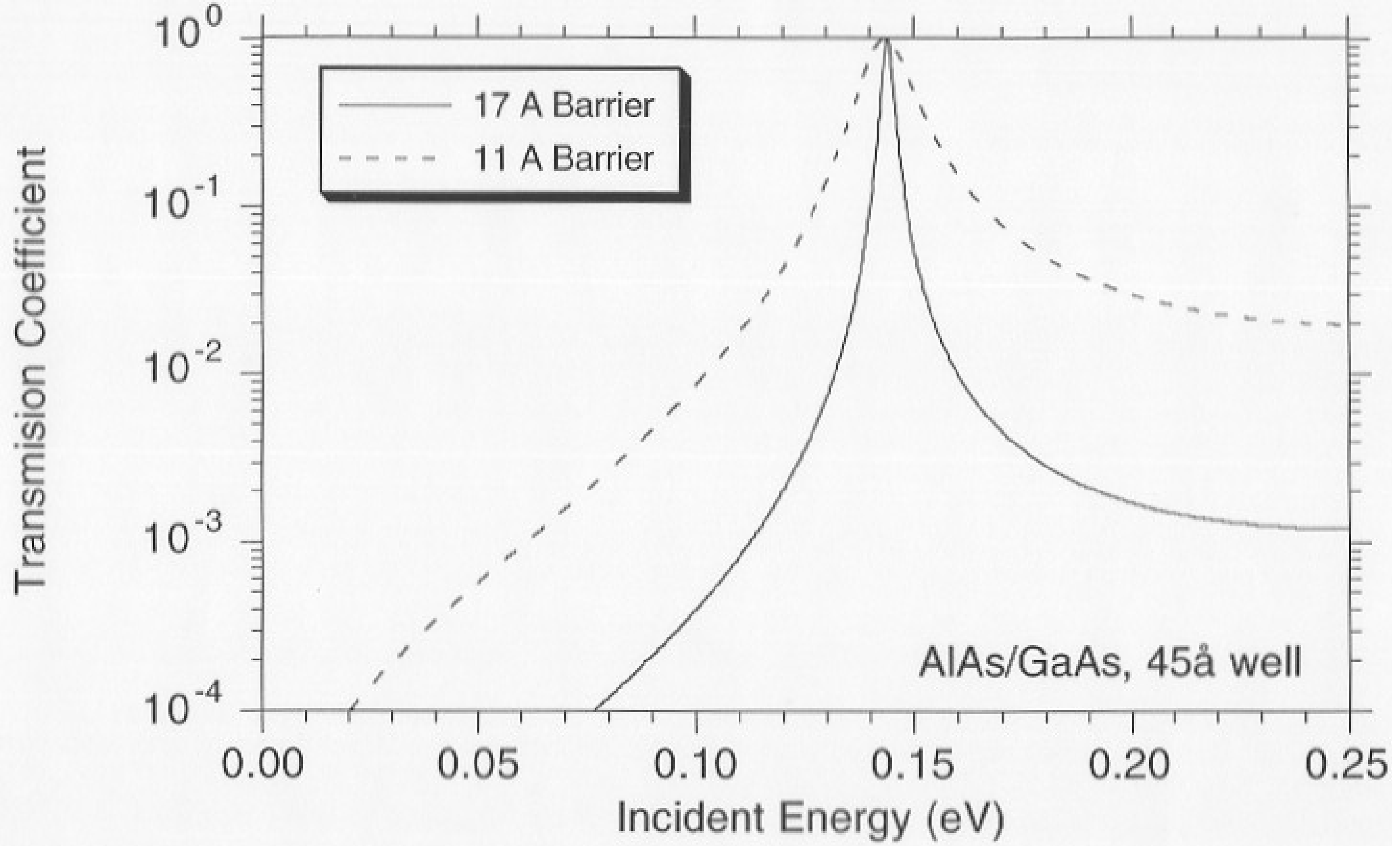
$$R(\omega) = R_s - \frac{R_n}{1 + \omega^2 R_n^2 C^2}$$

$$R(\omega_{\max}) = 0$$

$$\omega_{\max} = \frac{1}{R_n C}\sqrt{\frac{R_n - R_s}{R_s}}$$

RTD oscillators have been demonstrated to 712 GHz

Well Transmission Probability vs Energy



Quantum Well Inductance

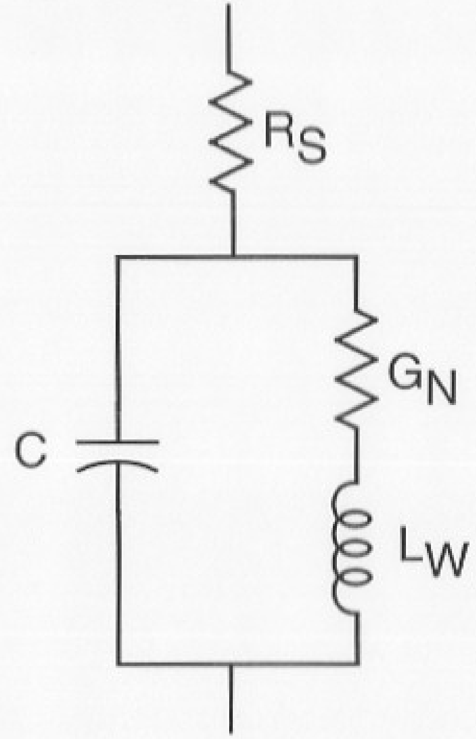
Transit time through well:

$$\tau = \frac{2\hbar}{\Delta E}$$

ΔE is the F.W.H.M. of the transmission probability

Equivalent inductance:

$$L_W = \frac{\tau}{G_N}$$

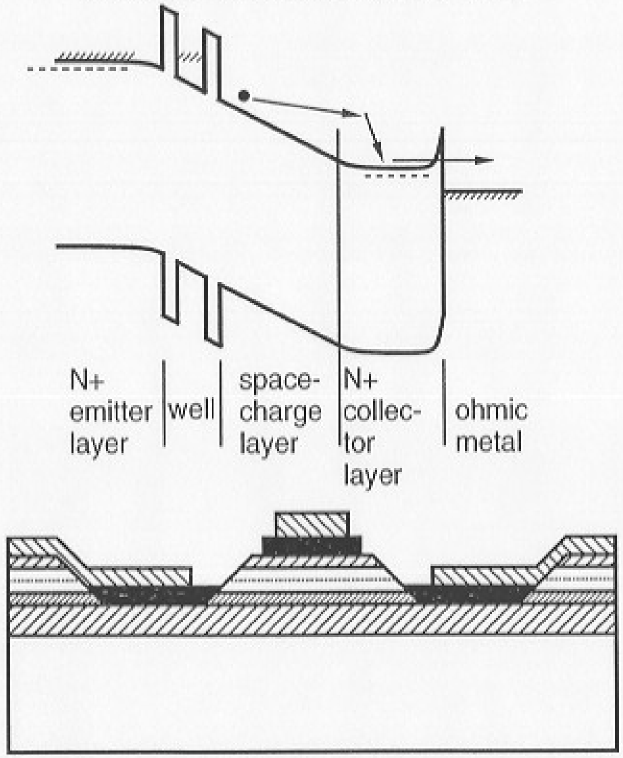


- In the negative resistance region G_n and L_W are negative.
- f_{max} is decreased
- Space charge transit time $\tau_t = d_{\text{space-charge}} / v_{\text{electron}}$ also effects $f_{\max}$, but

with $d_{\text{space-charge}} \cong 500$ å, $v_{\text{electron}} >> 10^7$ cm/sec and $\tau_t \approx 100$ fs

Schottky-Collector Resonant Tunnel-Diodes

ohmic-contacted RTD

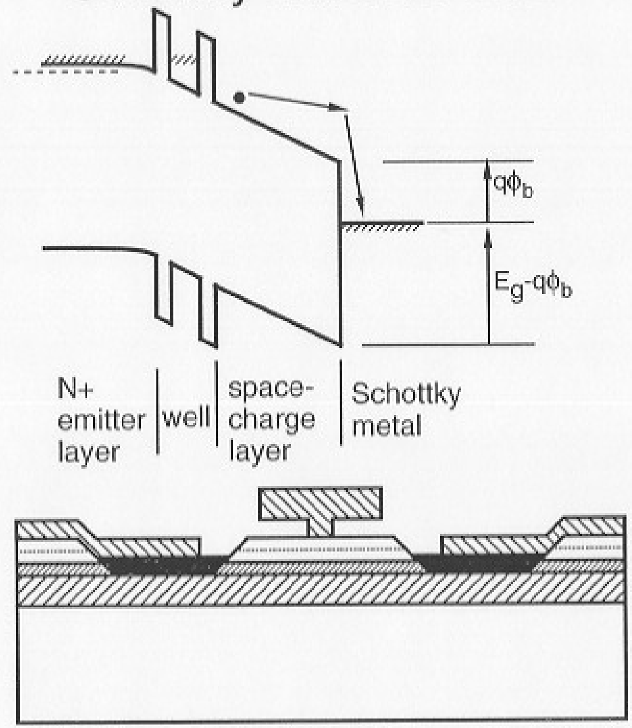


Schottky and interconnect metal

N+ emitter layer

N+ buried layer, N+ top contact layer

Schottky-collector RTD



semi-insulating GaAs

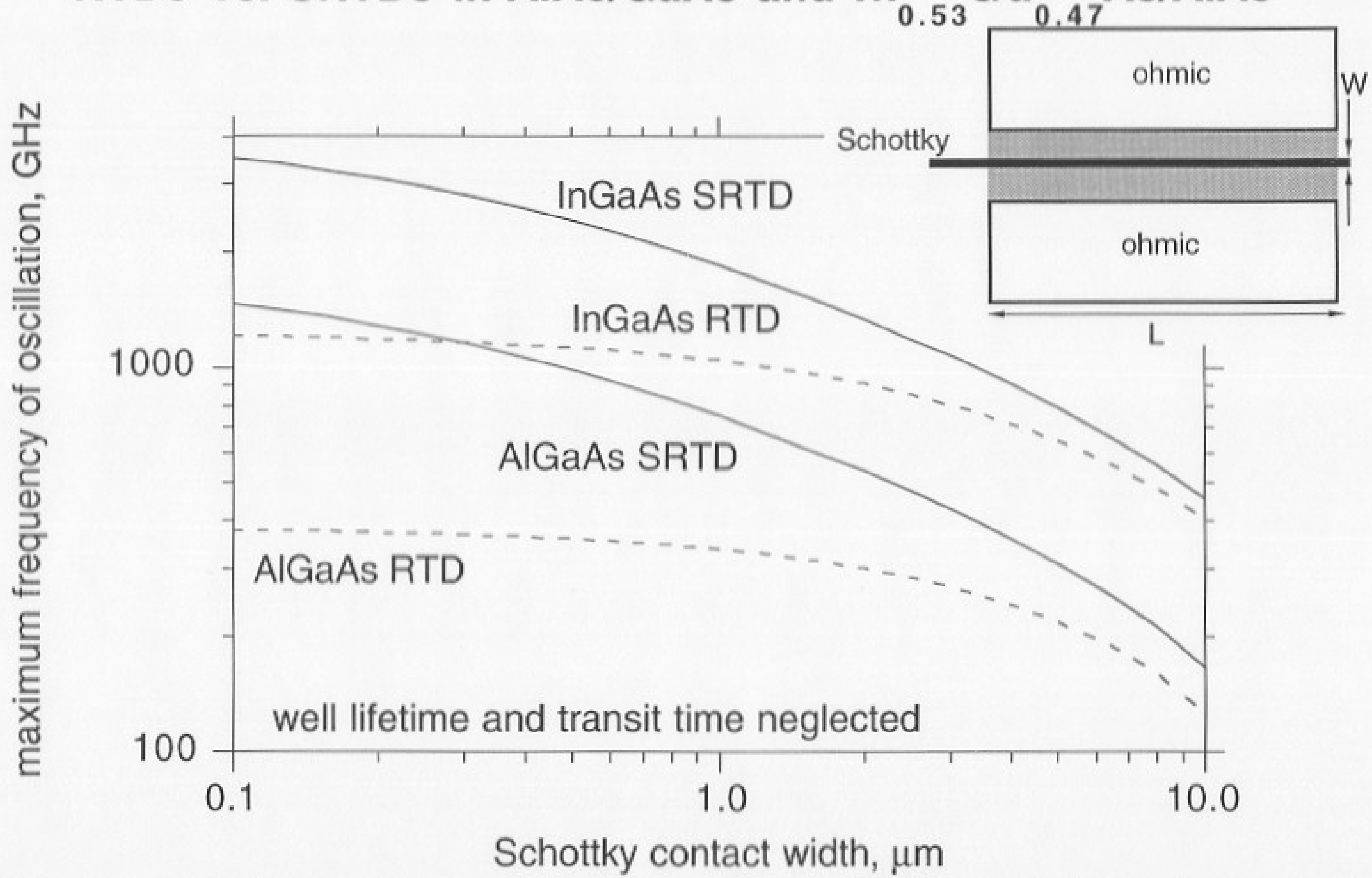
ohmic metal

quantum well

Top ohmic contact is eliminated. Decreased Rs, increased fmax

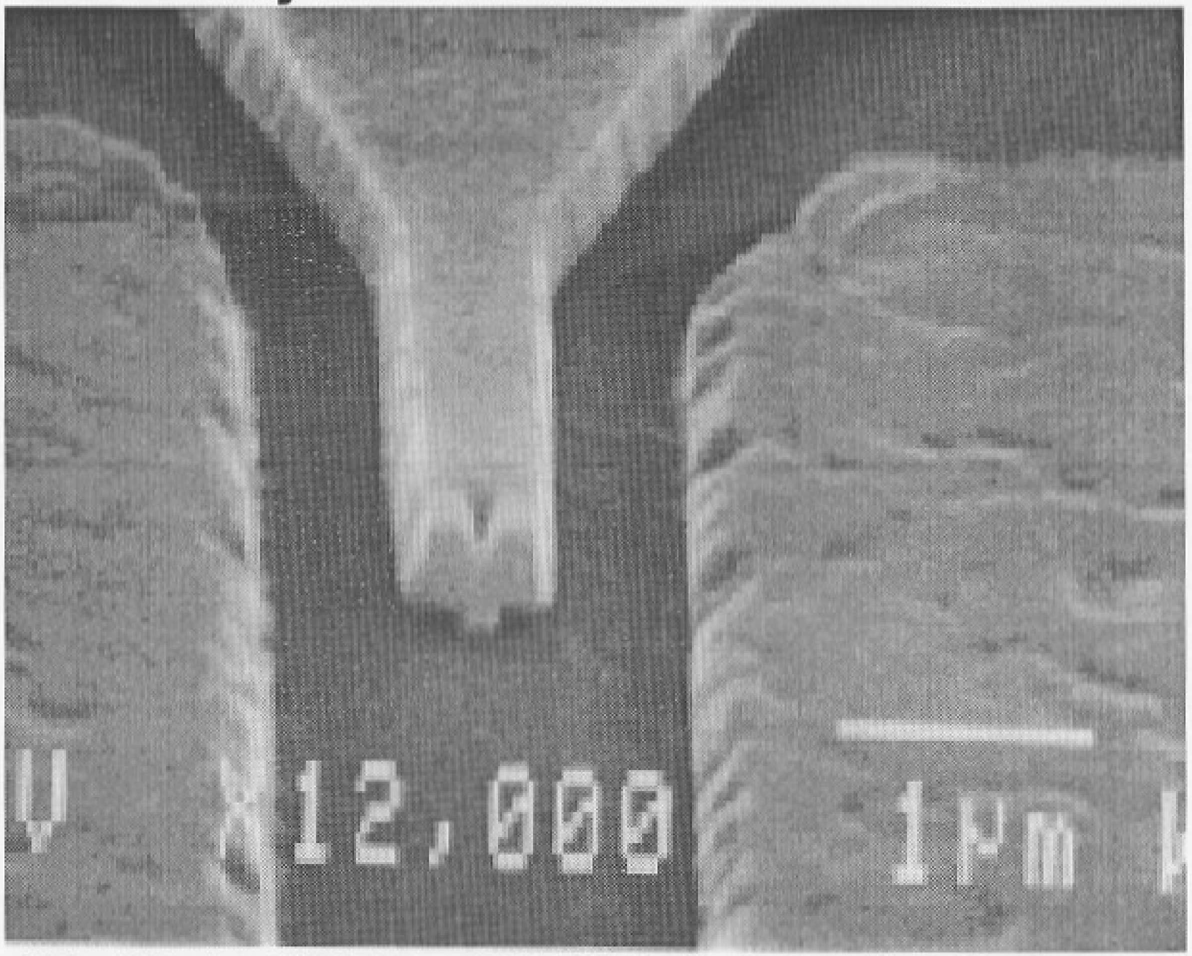
Bandwidth of Submicron Schottky-Collector RTDs

RTDs vs. SRTDs in AlAs/GaAs and $In_{0.53}Ga_{0.47}As/AlAs$



- Scaling to submicron dimensions increases RTD periphery/area ratio
- Periphery-dependent parasitic resistance terms driven towards zero (bottom ohmic contact resistance, buried N+ layer)

Schottky-Collector RTDs for 0.3-3 THz Oscillators



0.12-µm AlAs/InGaAs/InP device

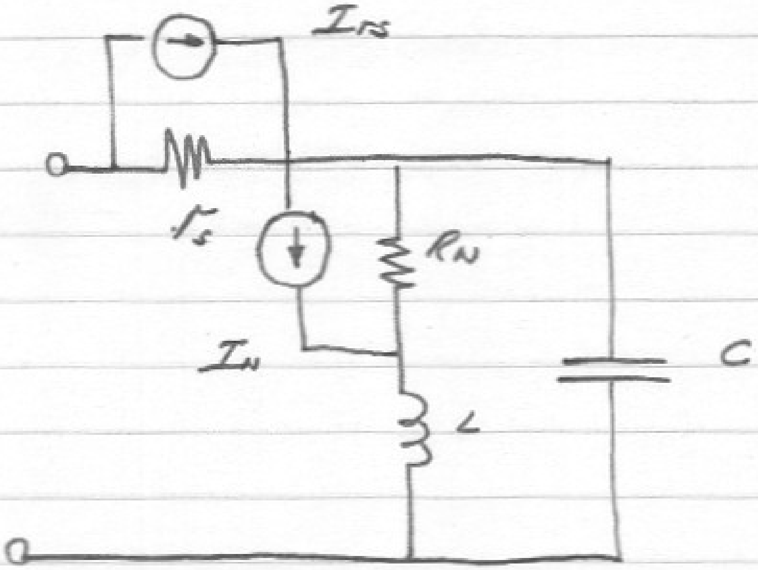
•Schottky (metal) electron collector, 0.1 -µm geometry.

•Greatly reduced series resistance, large increase in f_{max}

AlAs/GaAs SRTDs: 900 GHz f_{max} estimated
InGaAs/AlAs SRTDs: 2.2 THz f_{max} estimated
Application: 0.3-1.5 THz quasi-optical power oscillator arrays

So, in terms of externally observable parameters,

our RTD model is:



L, C, r_s as before,

$$S_{I_N I_N}(f) = 2q I_{dc} \left[1 - (\tau_{sc} + \tau_g) / \tau_{RC} \right]^2$$

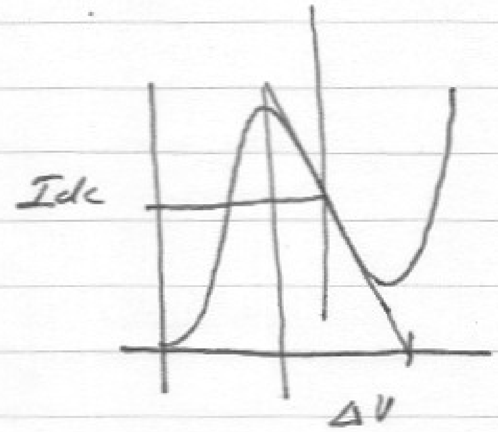
τ_{RC} negative in NDR!

so the "noise temperature" of R_N becomes:

$$T_{eq} = \frac{2q\,I_{dc}}{kT} R_N \left[1 - (\tau_{sc} + \tau_g)/\tau_{RC}\right]^2$$

note that $R_N \propto W$!

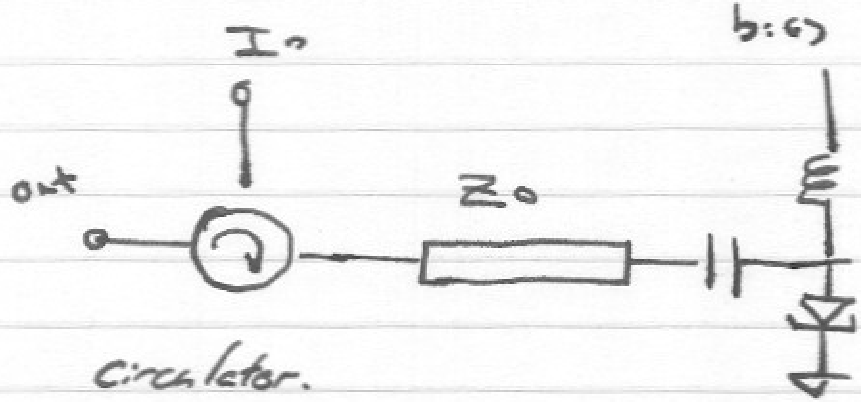
$=$



Low noise requires small W and C

high peak/valley current ratio...

Tunnel diodes are used as amplifiers thus:



Amplification is obtained from the reflection gain, eg the reflection magnitude is >1 because the RTD terminal impedance is negative.

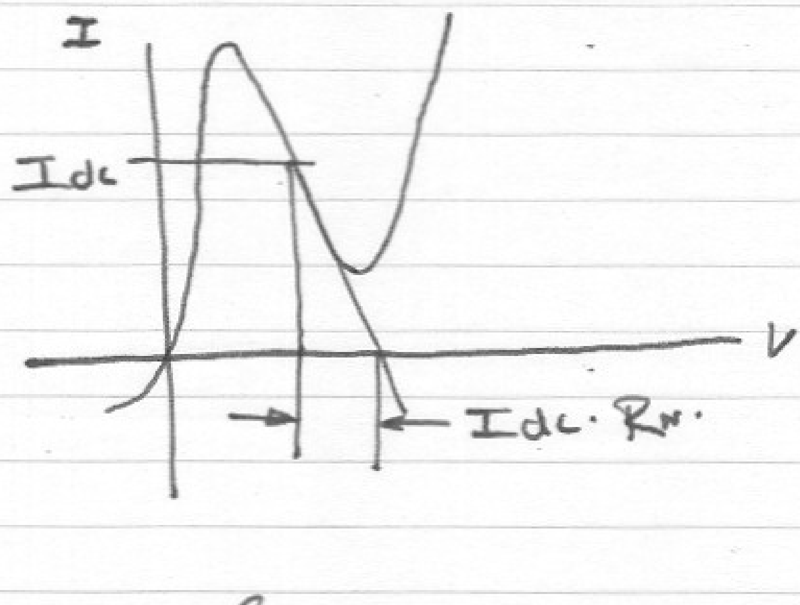
$$\Gamma = \frac{1 - G Z_0}{1 + G Z_0} \; ; \; |\Gamma| \to \infty \text{ as } G \to -1/Z_0.$$

Noise Measure of the reflection amplifier

is

$$M = \frac{q\, I_{dc} R_N}{2kT_0}\left[1 - \frac{\tau_{sc} + \tau_g}{\tau_{RC}}\right]^2$$

$$= \frac{I_{dc} R_N}{(2kT_0/q)}\left[1 - \frac{\tau_{sc} + \tau_g}{\tau_{RC}}\right]^2$$

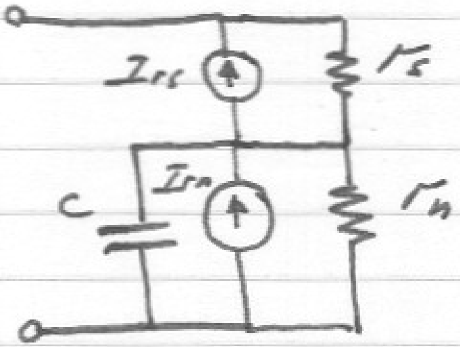


Key parameters for low noise are high PVR

and Thin ~~wet~~ space-charge region.

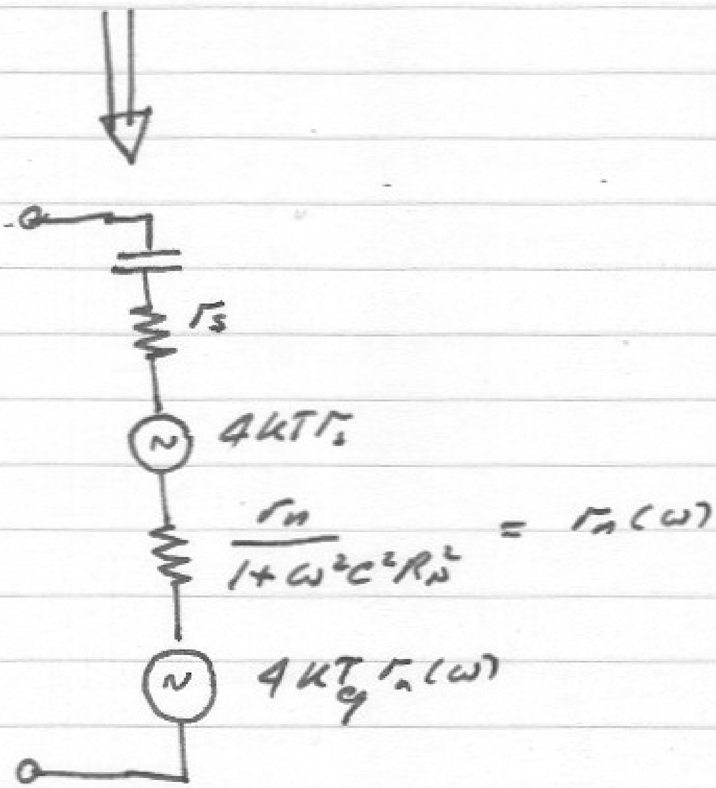
Lets find the frequency dependant noise

assuming $\tau_{gw} + \tau_{sc} \ll \sqrt{R_n R_s}\, C$.



I_{rs}: $4kT/R_s$

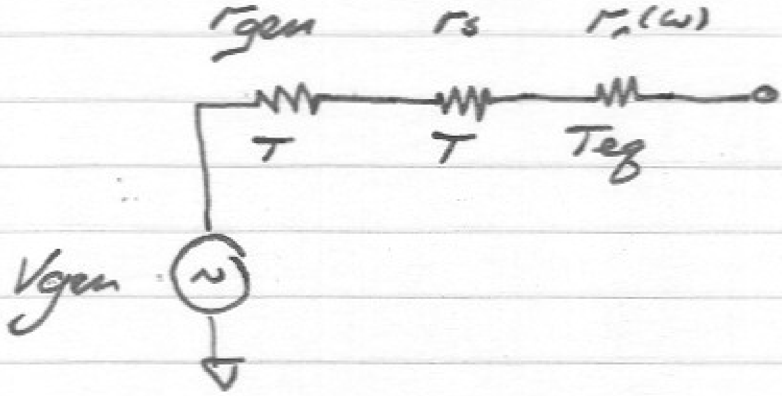
I_{RN}: $4kT_{eq}/|r_n|$



$$M = \frac{|r_n(\omega) - r_s| + |r_n(\omega)| T_{eq}/T}{|r_n(\omega) - r_s|}$$

$$\cong \frac{|R_N| - r_s \omega^2 C^2 |R_N| + |R_N| T_{eq}/T}{|R_N| - r_s \omega^2 C^2 |R_N|}$$

Hook this in series with a ~~ready~~ signal generator



$$F = \frac{4kT r_s + 4kT_{eq} r_n(\omega) + 4kT r_{gen}}{4kT r_s}$$

$$= 1 + \frac{r_{gen} + r_n(\omega) \cdot T_{eq}/T}{r_s}$$

gain is infinite for $r_{gen} + r_s + r_n(\omega) = 0$

$$r_{gen} = -r_n(\omega) - r_s$$

$$F_\infty = 1 + \frac{|r_n(\omega) - r_s| + r_n(\omega)\, T_{eq}/T}{|r_n(\omega) - r_s|}$$