Interface Roughness in Resonant Tunnelling Diodes for Physically Unclonable Functions

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Counterfeiting costs the semiconductor industry billions annually[1], and Physically Unclonable Functions (PUFs)[2, 3] are a solution to this that has garnered interest, which works by uniquely identifying chips they are attached to. Resonant Tunnelling Diodes (RTDs) are one such device being investigated for PUF applications[2, 3]. PUFs depend on device variability to provide an unpredictable output response to a given challenge input, and multiple of these challenge-response pairs can compose a random and unique 'fingerprint', to identify devices against a database. Interface Roughness (IR) along heterostructure interface are one such source of stochastic variability of RTDs, which we have included by varying the GaAs/$Al_{0.3}Ga_{0.7}As$ interfaces in the 'smooth' 55nm×10nm×10nm RTD shown in Fig.1(a). This IR leads to $Al_{0.3}Ga_{0.7}As$ barriers as shown in Fig.1(b), and causes variation in both the quantum well[3] and barriers[4], which RTDs are highly sensitive to.

We carried out simulations using the custom and modular Nano-electronic Simulation Software (NESS)[5] software, using a Non-equilibrium's Green's Function (NEGF) solver to capture quantum tunnelling behaviour. 25 devices were randomly generated and simulated in the ballistic regime for different correlation length $\mathrm{L_C}$ and root-mean-square roughness asperity Δ_{RMS}.

Fig.2 displays colourmaps of PVCR and voltage and current standard deviations of resonant peaks, or local maxima. Δ_{RMS} has a greater effect on the parameters shown than $\mathrm{L_C}$, and there seems to be a trade-off between decreasing Peak to Valley Current Ratio (PVCR) and increasing voltage and current standard deviations as Δ_{RMS} is increased. $\mathrm{L_C}$=7.5nm and Δ_{RMS}=0.3nm balance PVCR with moderately large standard deviations, which fits the purpose of using RTDs as PUF components[2], by being able to encode information in whether the current and voltage of the resonant peak is greater or less than the centre of the current and voltage distributions. This also roughly matches the parameters used in [6], and Δ_{RMS}=0.3nm is close to the monolayer thickness of GaAs and $Al_{0.3}Ga_{0.7}As$.

Fig.3 shows the significant variability of current-voltage curves and distribution of resonant peak current-voltage peaks for $\mathrm{L_C}$=7.5nm and Δ_{RMS}=0.3nm. We fitted with normal curves and used the mean of these to split the distribution into quadrants. With further simulations, it would be possible to assess the minimum bits of information that could be encoded in an RTD with min-entropy $-\log_2 n_{max}/N$. Here n_{max} would be the number of resonant peaks in the quadrant most densely populated as seen in Fig.3(b), and N the total number of devices. Multiple RTDs would then be combined on a chip to create a PUF encoding a certain amount of information[2] for identification.

We have explored how varying $\mathrm{L_C}$ and Δ_{RMS} for IR along GaAs/$Al_{0.3}Ga_{0.7}As$ interfaces in RTDs changes the mean PVCR and the standard deviations in resonant peak voltage and current values. It was determined that $\mathrm{L_C}$=7.5nm and Δ_{RMS}=0.3nm balances PVCR with moderately large standard deviations, and briefly noted how this could be used to encode information quantified by min-entropy, allowing multiple RTDs be combined into a PUF. This research provides a direction for further research of RTDs for PUF applications.

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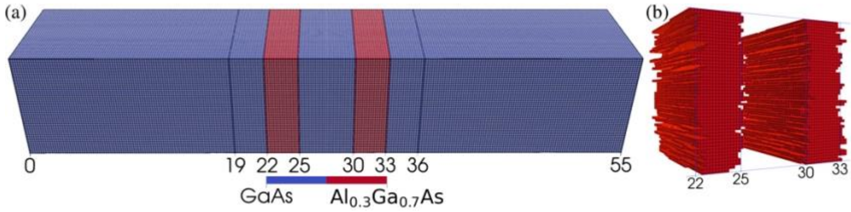
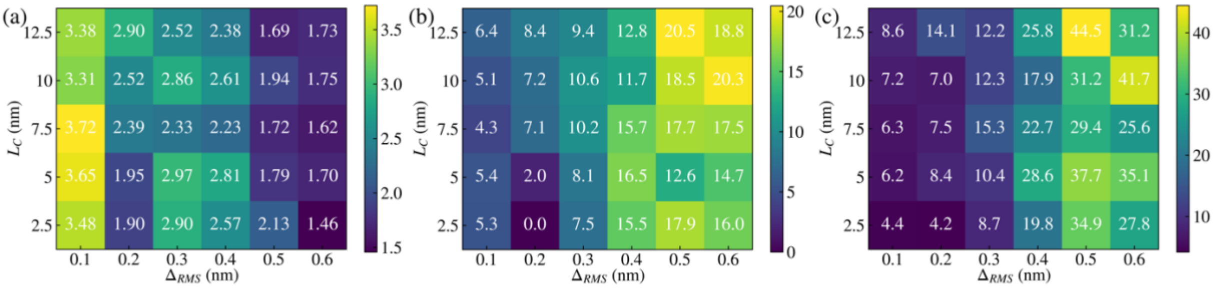


Figure 1: Fig(a) is a ‘smooth’ 55nm×10nm×10nm RTD composed of two 19nm long $2 \times 10^{18} cm^{-3}$ n doped GaAs source-drain regions and a central $5 \times 10^{15} cm^{-3}$ n doped region comprising two 3nm GaAs buffers, two 3nm $Al_{0.3}Ga_{0.7}As$ and a 5nm GaAs quantum well. Fig(b) shows $Al_{0.3}Ga_{0.7}As$ barriers with randomly generated IR of L_C=7.5nm and Δ_{RMS}=0.3nm, following an exponential roughness model[7].



(a)

L_C (nm)	0.1	0.2	0.3	0.4	0.5	0.6
12.5	3.38	2.90	2.52	2.38	1.69	1.73
10	3.31	2.52	2.86	2.61	1.94	1.75
7.5	3.72	2.39	2.33	2.23	1.72	1.62
5	3.65	1.95	2.97	2.81	1.79	1.70
2.5	3.48	1.90	2.90	2.57	2.13	1.46

(b)

L_C (nm)	0.1	0.2	0.3	0.4	0.5	0.6
12.5	6.4	8.4	9.4	12.8	20.5	18.8
10	5.1	7.2	10.6	11.7	18.5	20.3
7.5	4.3	7.1	10.2	15.7	17.7	17.5
5	5.4	2.0	8.1	16.5	12.6	14.7
2.5	5.3	0.0	7.5	15.5	17.9	16.0

(c)

L_C (nm)	0.1	0.2	0.3	0.4	0.5	0.6
12.5	8.6	14.1	12.2	25.8	44.5	31.2
10	7.2	7.0	12.3	17.9	31.2	41.7
7.5	6.3	7.5	15.3	22.7	29.4	25.6
5	6.2	8.4	10.4	28.6	37.7	35.1
2.5	4.4	4.2	8.7	19.8	34.9	27.8

Figure 2: Colourmaps of distribution values for different L_C and Δ_{RMS}. Fig(a) is the mean of PVCR, and Fig(b) and Fig(c) are respectively the voltage (millivolts) and current (nanoampere) standard deviation of fitted normal curves to the distribution of the current-voltage of the local resonant peak values as seen in Fig.3.

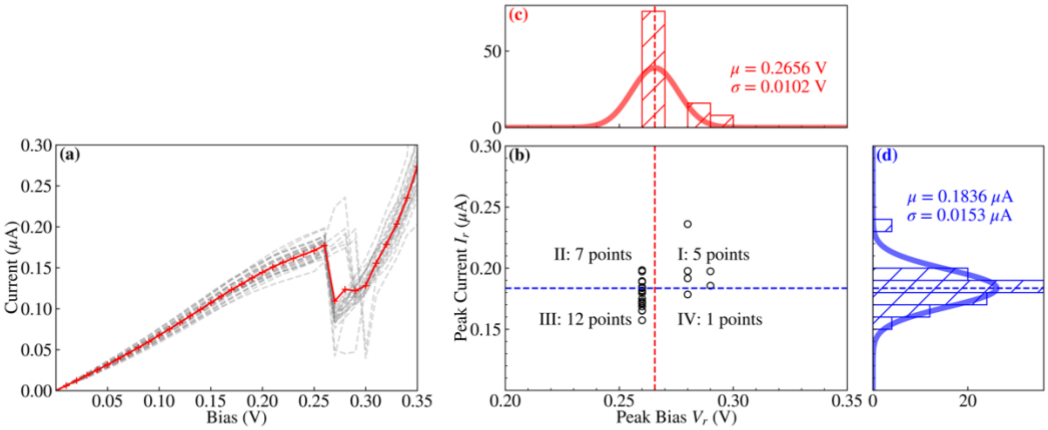


Figure 3: Fig(a) shows current-voltage plots for 25 randomly generated RTDs with exponential IR of L_C=7.5nm and Δ_{RMS}=0.3nm as grey dashed lines. The mean current-voltage characteristic is shown as a solid red line with plus markers. The resonant peak, or local maxima, of each current-voltage characteristic is shown in Fig(b) and is split into 4 quadrants by the mean of fitted normal distributions for the voltage and current distributions as seen in Fig(c) and Fig(d) respectively. Fig(c) and Fig(d) also show histograms for occurrence of resonant peak values.

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