Process Control in GaAs Manufacturing Using Chua's Circuit

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Abstract

This paper provides the measurement results of the Chua's circuit manufactured using an InGaAs pHEMT process. The designed circuit was capable of producing both, harmonic and chaotic oscillations. The circuit's equilibrium points were estimated from the measured time-domain signals and the variation in the coordinates of those points was studied. It was found that equilibria depend on supply voltage and reticle location implying high sensitivity of the designed circuit. Equilibrium points are shown to be able to give insight into the manufacturing process state and variation of thereof.

INTRODUCTION

The control of the integrated circuits manufacturing process is performed using Process Control Monitors, or PCMs. The PCM contains separate devices whose characteristics are measured and based on the measurement results, the decision about the functionality of the main circuit, located on the same reticle is made. It is readily acknowledged for the GaAs manufacturing process that with growing complexity of the circuits, PCMs start to be a less reliable predictor. Namely, the correlation between the performance of the PCM and nonlinear performance of the main circuit has weakened meaning that acceptable results of PCM measurements don't guarantee the good performance of the main circuit. A possible reason for this is the fact that the PCM only allows measurements of linear circuit characteristics, while non-linear effects may have rather strong impact on the circuit's performance. Therefore, it is desirable to have a small and simple nonlinear circuit in place of, or along with a PCM which can strengthen the correlation between the monitor circuit and the main one.

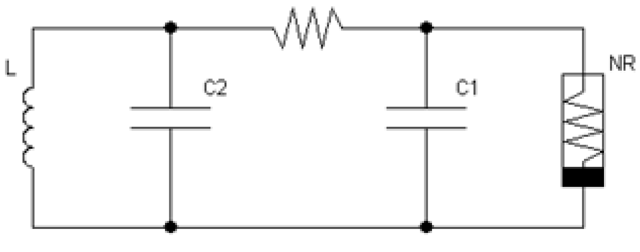

Figure 1. Chua's circuit schematics

In this paper we present the measurements of a Chua's circuit designed specifically for GaAs pHEMT manufacturing and discuss its applicability for the role of a circuit control monitor, CCM. Chua's circuit was the first electronic circuit to demonstrate chaotic behavior [1], its schematics is shown in Figure 1. The nonlinear resistor (NR) is a crucial component for obtaining chaotic signals. Its current-voltage characteristic has to be negative somewhere on the curve. In this case, the NR was implemented using two cross-coupled inverters which allowed generating smooth nonlinearity [2]. Being a chaotic system, Chua's oscillator is very sensitive to the values of its components and this fact along with it being very small in size makes it a good candidate for a CCM.

METHODS

The circuit was designed using AWR Microwave Office Design Environment. It contains two MIM capacitors, one spiral inductor and one TFR resistor, the active part of this circuit, a nonlinear resistor is composed of 8 pHEMT transistors and 2 pHEMT diodes. The circuit was manufactured employing a 0.15 μm production GaAs pHEMT process available from WIN Semiconductor. The micro-photography of the layout is shown in Figure 2 and its approximate dimensions are 1085 μm by 860 μm. The circuit

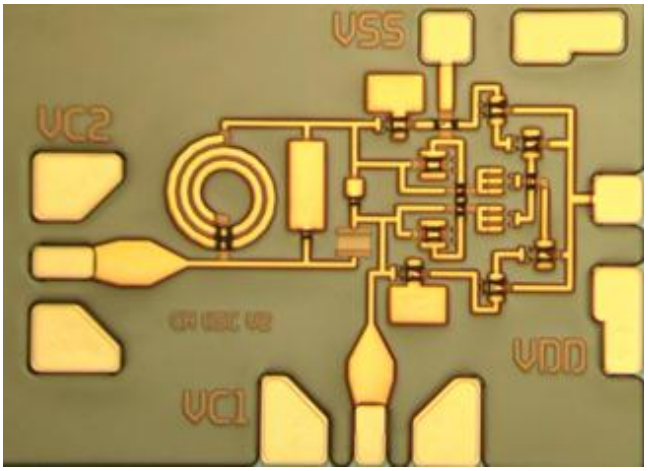

Figure 2. Designed circuit layout

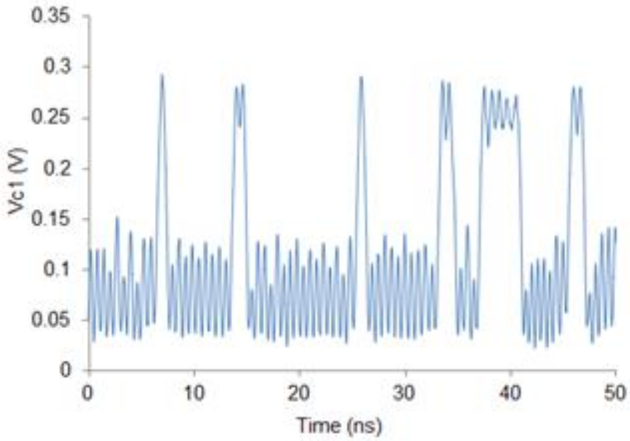

Figure 3. Chaotic oscillations of voltage across capacitor C_1

was measured on-wafer using dual voltage supply for biasing the NR and Agilent Technologies DSO9104A oscilloscope was used for monitoring the C_1 voltage in time domain. Measurements showed that with different bias conditions, the circuit can generate both chaotic signals as well as harmonic oscillations. Period-doubling bifurcations route to chaos [3] was also observed when changing the bias voltage.

The analysis of the measured data series relied on the time lag method. This method of plotting single data series in a 2D phase space makes the observation of chaotic features easier. As the name of the method suggests, we plot the original time series versus its time-shifted copy. In other words, we plot the variable measured at time t versus the same variable measured at time t plus some time lag, τ. Time lag was chosen to be 62.5 ps as this value provides clear and readable phase portraits, however there is no specific reason for τ to be that exact number.

During the measurements a range of bias voltages which shifted the circuit's behavior from stable to chaotic oscillations was obtained. An example of chaotic oscillations for $V_{DD} = 5.9$ V and $V_{SS} = -2.5$ V is shown in Figure 3. As the bias voltage was swept, period-adding bifurcations leading to chaos were observed. With V_{SS} being kept constant at -2.5 V, V_{DD} was varied in the range from 5.3 V to 6.2 V (see Figure 4). This type of measurement was performed on several selected reticles with the measurements repeating themselves qualitatively.

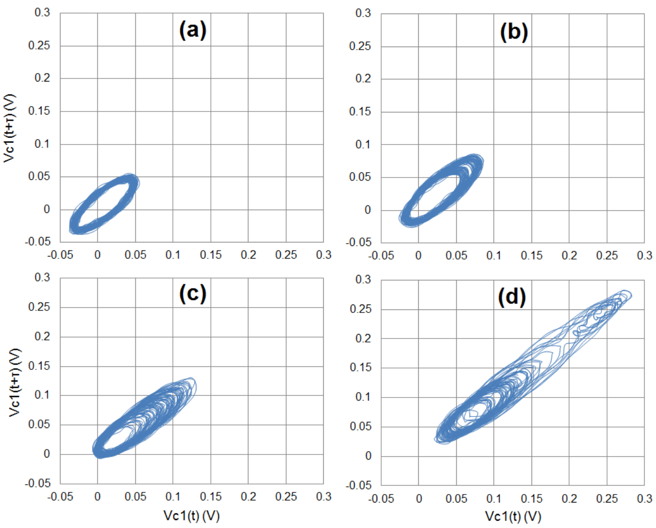

Figure 4. Bifurcations occurring with the increase of V_{DD} (a) - period-1 oscillations, (b) – period-2 oscillations, (c) – period-4 oscillations, (d) – chaotic double-scroll attractor

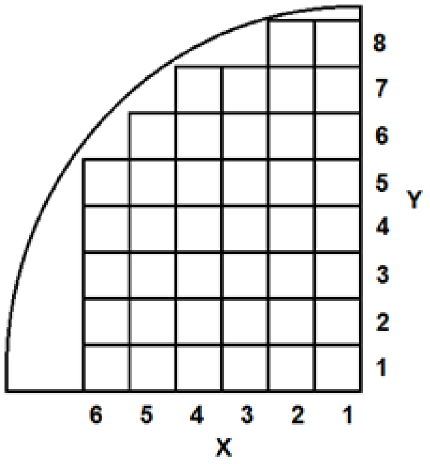

Figure 5. Reticles' coordinates on the quarter wafer

After embedding the V_{C1} into the phase space, we could estimate the coordinates of system's equilibrium points. Equilibrium points can be seen as points on the phase plot around which the trajectory rotates. Periodic orbits have one equilibrium point which in our case corresponds to the lower equilibrium point of a double scroll attractor [4]. From equations that govern the behavior of the circuit it is clearly seen that the location of those points mostly rely on the current-voltage characteristic of the NR [5]. This characteristic in its turn depends on the parameters of the transistors which are completely defined by the manufacturing process. That creates a link between the location of equilibrium points and the state of the manufacturing process. It should be noted here that the coordinates of equilibrium points were found visually using the data series. Due to noisy data, the coordinates couldn't be estimated automatically (using a computer algorithm) but were instead located manually. Although done carefully, manual processing leaves some space for measurement error, therefore results with this current CCM methodology describe processes qualitatively rather than quantitatively.

The reticles located on a quarter wafer were measured. The map of the wafer is depicted in Figure 5, it shows that the reticles are being addressed by their X and Y coordinates written down as [X, Y].

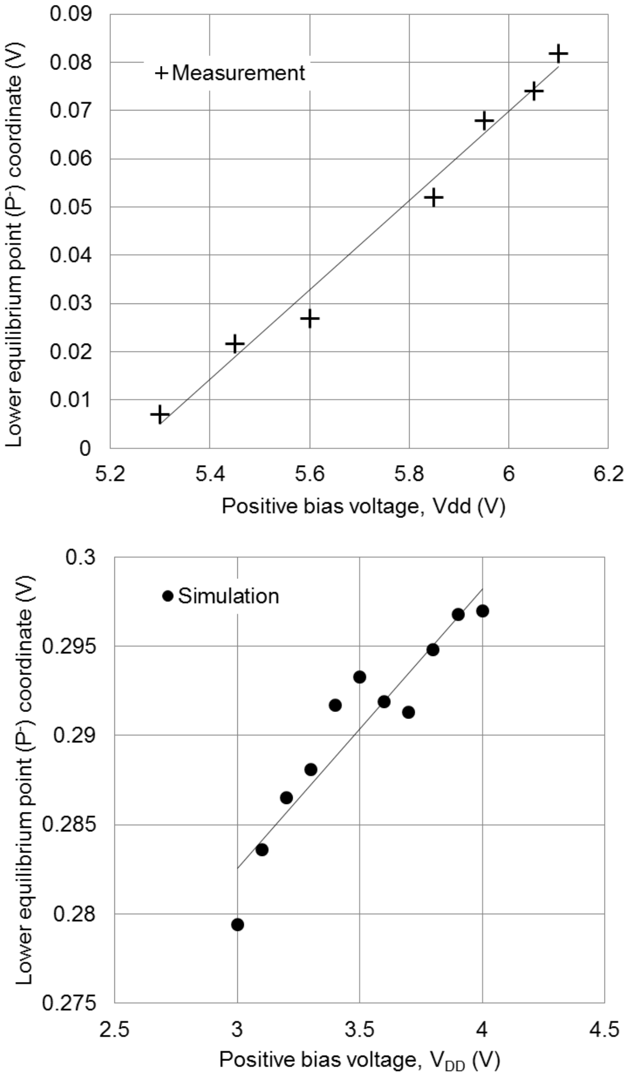

Figure 6. Relation between the equilibrium point coordinates and V_{DD} bias voltage from the measurements (top) from the simulation data (bottom)

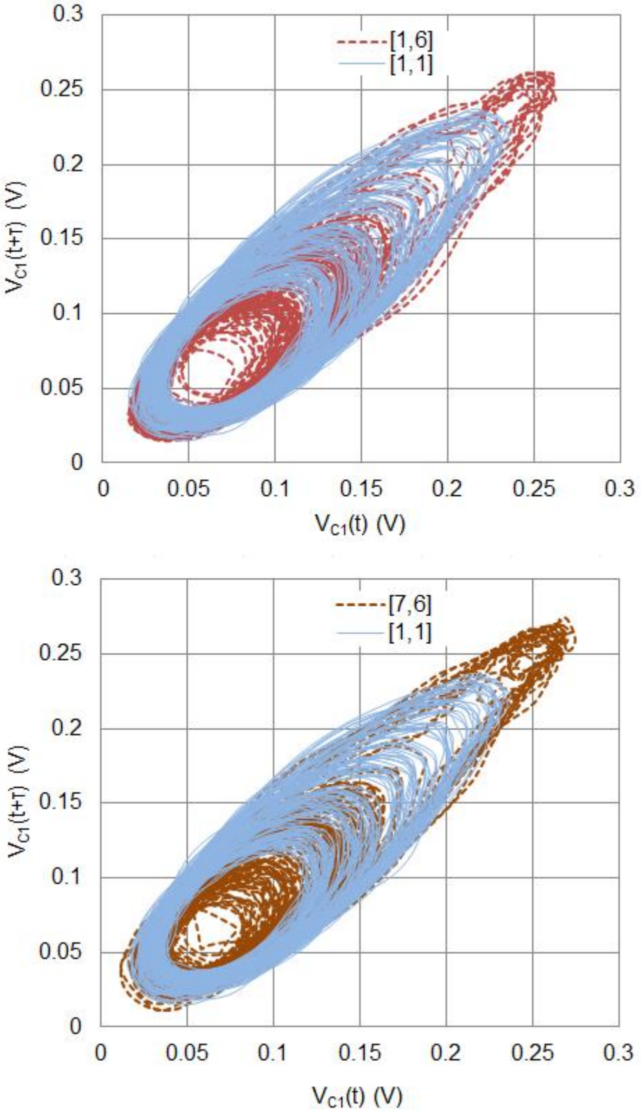

Figure 7. Comparison of attractors' equilibrium points for reticle in the center of the wafer [1,1] and reticles close to its edge [1,6], [7,6]

DISCUSSION

It can be seen from Figure 6 that the lower equilibrium point of the attractor was moving in the direction of higher voltages during the observation of bifurcations. Current-voltage characteristic of the NR depends on the bias voltage supplied and changes its shape as the voltage is increased. That leads to the relocation of equilibrium points. The observed trend agrees with the simulations performed for similar bias conditions. However, one should note the difference in scale for simulation and measurements meaning that the simulated circuit is less sensitive to bias conditions relative to the real one. The underlying cause for this is still under investigation.

A variation of equilibrium point coordinates was noticed for circuits located in different areas of the wafer. The bias conditions were kept constant with V_{DD} = 5.9 V and V_{SS} = -2.5 V. The change of the equilibria coordinates formed a linear trend from the center of the wafer towards its edges. As we can see from the attractors depicted in Figure 7, the coordinate of the lower equilibrium point tends to decrease for the circuits located closer to the edge of the wafer. The graphs shown in Figure 8 demonstrate the change in the coordinate of the equilibrium point as we move from the center of the wafer towards its edge. Two dot graphs show the horizontal and vertical variations. As it can be seen, the trend is more noticeable for the horizontal (along the x-coordinate) lines, however vertical data (along the y-coordinate) being more noisy still contains the same trend. Also it can be seen, that coordinates of equilibrium points for each of the three lines are closely correlated with each other.

The movement of equilibrium points is caused by the shift of multiple parameters, according to the basic theory for the

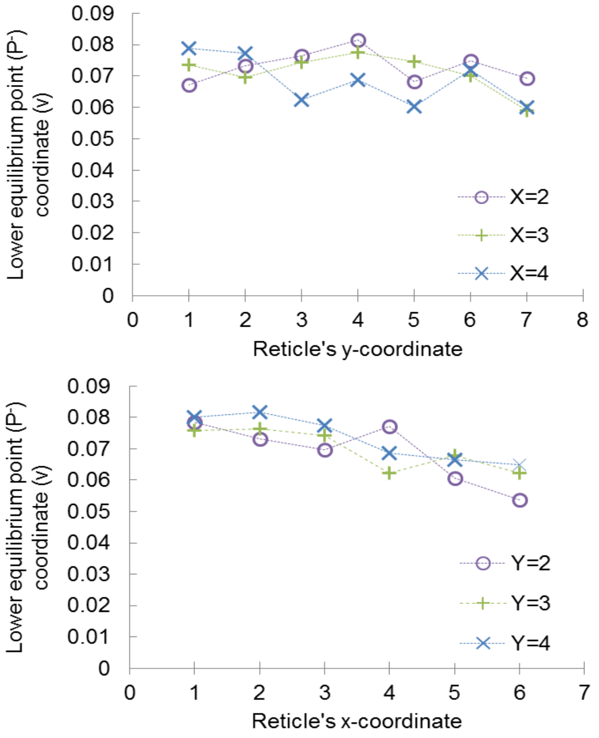

Figure 8. Equilibrium points of the circuits across the wafer

Chua's circuit. To shed more light on this, a simulation experiment was carried out. The gate widths of all the transistors were scaled by the factor *k* ranging from 0.97 to 1.03. The scaling of gate width effectively leads to the change of transistor transconductance. The higher the gate width is, the higher the transconductance. Simulation of the circuit in AWR showed that increased transconductance leads to the equilibrium points coordinates moving higher (Figure 9).

CONCLUSIONS AND FUTURE WORK

Measured dependence of the equilibrium point coordinates and the bias voltage of the NR showed good agreement with theory and simulations.

Simulation of the equilibria relation with the gate widths of the transistors helped to justify the declining trend of the equilibrium point coordinates from the center towards the edge of the wafer. It could arise from the decrease of the transconductance of the transistors. However, that doesn't imply that the cause for equilibrium points shift was the gate width modulation. The trend suggests that there is a fluctuation of a certain manufacturing parameter across the wafer and the ultimate goal of the CCM based on the chaotic Chua's oscillator is to be able to pinpoint the exact parameters. A reliable method of defining the equilibrium point coordinates has to be developed as well.

The circuit in its present form may be sensitive to the parameters of the transistors but currently it's impossible to distinguish which specific parameter had been altered. However using this circuit with an existing PCM may give a better insight into the functionality of actual circuits.

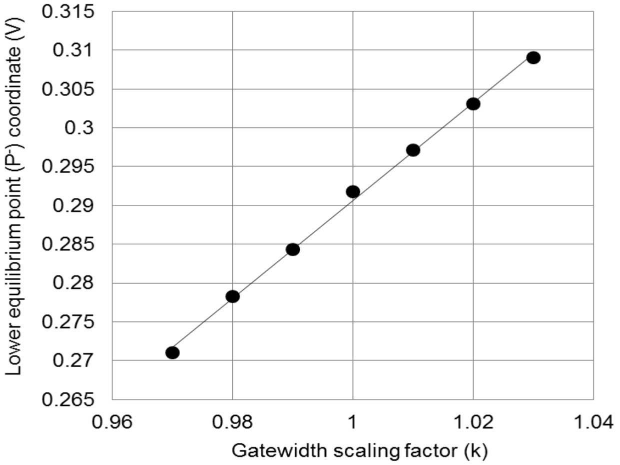

Figure 9. Simulated relation between equilibrium point coordinates and the gate width of the pHEMTs

A measurement technique has to be developed to allow as many manufacturing and transistor parameters to be unambiguously estimated from the tests. Further experiments for correlation between the Chua's circuit performance and performance of other circuits are required to obtain the statistical significance of the CCM sensitivity.

ACKNOWLEDGEMENTS

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ACRONYMS

PCM: Process Control Monitor
CCM: Circuit Control Monitor
NR: Nonlinear Resistor
pHEMT: Pseudomorphic High-electron-mobility Transistor
MIM: Metal – Insulator – Metal
TFR: Thin Film Resistor