WHAT IS ELECTRONIC DEVICE MODELING ?

AND ITS IMPORTANCE FOR THE DESIGN OF TODAY'S INTEGRATED CIRCUITS

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electronic tubes, transistors, semiconductors, integrated circuits, analog & digital circuits, bread board design, circuit design by computer simulations, electronic device modeling

C O N T E N T S:

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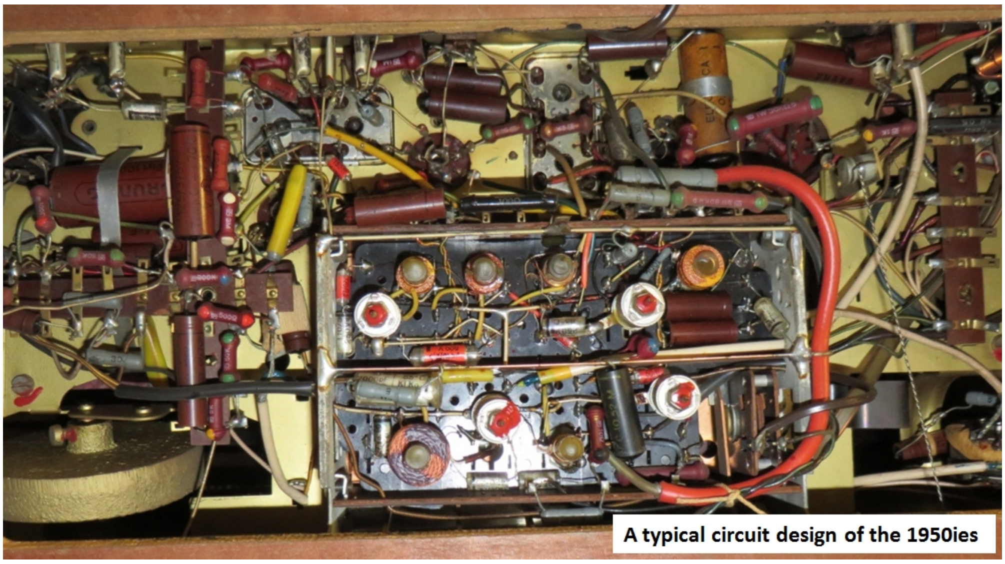
- Electronic Circuit Evolution

Integration of Electronic Components
The importance of electronic device modeling can best be understood when recapitulating the evolution of electronic circuits. Let's take an FM/AM radio as an example.

In the 1950ies, radio receivers had been relative large accessories in people's living rooms. Their electronic components were electronic tubes, and so-called passive devices like resistors, capacitors and inductors.

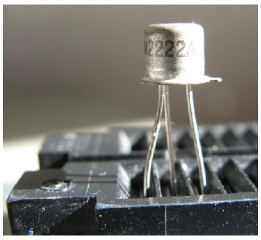
The Grundig Type 3012 AM/FM radio receiver of the 1950ies, shown on the left, is a good example. It featured listening to radio stations distributing their programs by 'Amplitude Modulation' [AM] in the 'Long Wavelength' Band [LW], 'Medium Wavelength' Band [in German 'Mittelwelle'], 41m and 49m 'Short Wavelength' [SW, in German 'KW' Kurzwelle]. Additionally, it offered already listening to the newly introduced, modern Frequency Modulation (FM) scheme with ultra-clean sound, and practically no transmission noise any more. A sound equalizer for individually boosting the low, medium and high tones was already state of the art. So, when compared to today's radio features, the only missing functionality is the stereo sound, which was introduced later in the 1960ies.

A look at the above Grundig radio receiver from the opened back side is given in the next picture. On the top are the loud speakers. The metal chassis at the bottom hosts the larger electronic components on its top, like the tubes (the glass cylinder on the left, two smaller tubes can be found in the middle) and the transformers and capacitors in their aluminum shieldings. On the bottom side of this electronic device chassis, accessible from the bottom of the wooden radio mainframe, are the very electronic components, like the smaller resistors, capacitors and inductors. They are mounted towards the bottom to prevent from accumulating dust, what would have affected the electronic performance, and -not to forget- could also lead to inflammation due to the heated tubes.



A typical circuit design of the 1950ies

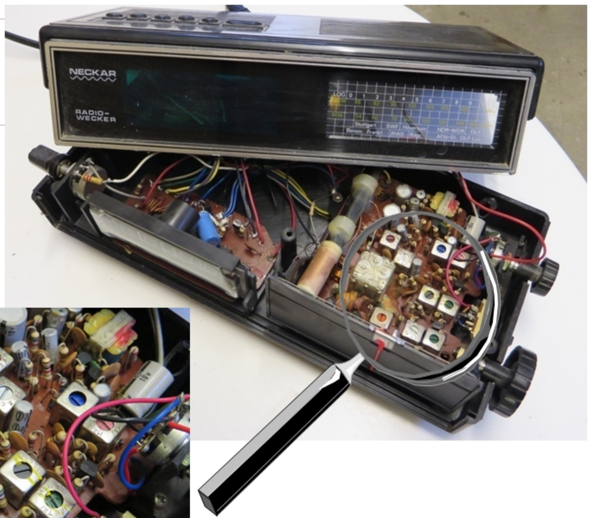
A more detailed view of the radio's electronic circuitry, accessible from the bottom, is shown above: the resistors, capacitors and inductors are connected pretty much zigzag to the soldering points. A repair of defect components is quite easily possible. Also, when thinking of how such radio circuits have been designed by the development engineers, it becomes obvious that they were able to add, remove or exchange components with the help of a simple soldering iron. The interconnections between the components were made by extra wires, or simply by using the wires at both sides of the component themselves. The engineering skills were mainly experience, best-practice know-how, and certainly also try-and-error.



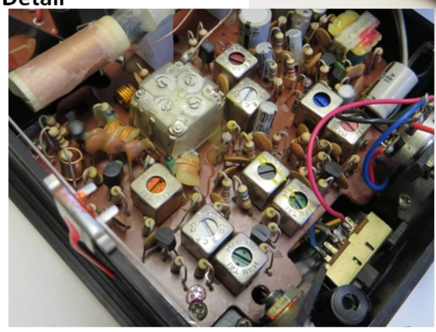
In the late 1960ies, the tubes had been replaced by the much smaller and much less power consuming transistors. At that time, as shown on the right, transistors had been individual components, in a metal or plastic package of about 5mm diameter.

The component fixation and interconnection was now done by using so-called 'Printed Circuit Boards' [PCB]. This is depicted below with the example of an alarm-clock radio of the mid-1970ies.

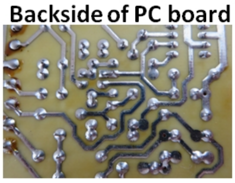
Circuitry of a FM/AM Radio in the 1970ies



Detail



Backside of PC board



The circuit board, made from epoxy, holds on one side the components, while the back side is used for connecting the components with cupper areas etched out of the copper foil PCB layer. The circuitry therefore is now much more compact and the component placing and later soldering can already be done by automates.

The circuit development engineer of that time was still able to scratch cupper connections, and add new connections by soldering cables. The manipulation of the components was possible by unsoldering and replacing them. Once the new design became mature, a new PCB board with improved cupper connections and fixations/soldering holes for the electronic components was manufactured, and the improved radio receiver version could be produced in series.

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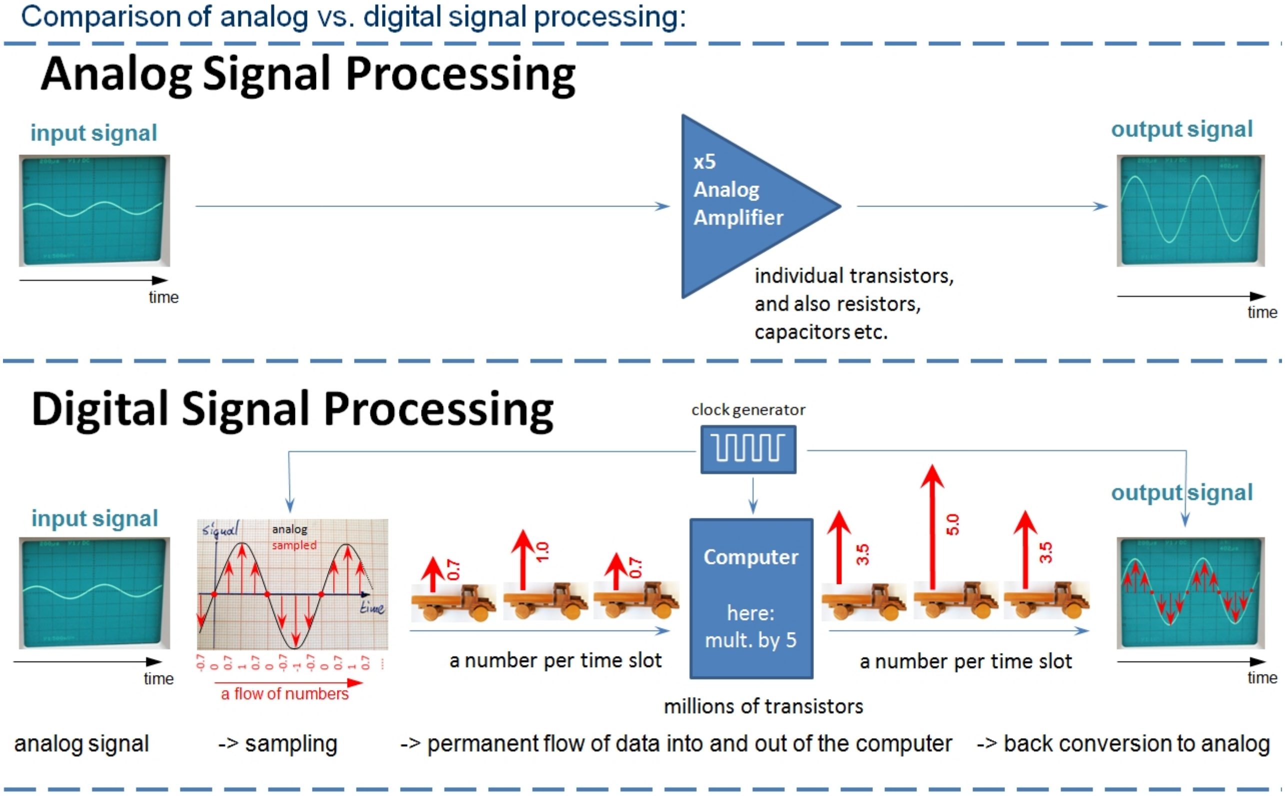
From Analog To Digital

It is very important to note that the technology revolution from electronic tubes via individual transistors to finally 'Integrated Circuits' [ICs] was done in two steps. While the invention of the transistor as an *individual component* dates back to the late 1940ies, the early 1960ies are the start of *component integration*, all on a single chip. Millions of resistors and capacitors could now be manufactured *on the same semiconductor substrates as the millions of transistors and diodes*, and, of course, be interconnected as well. This was a huge revolution, because since then, the manufacturing cost factor for the individual electronic devices, especially for the smaller and smaller components, went down by also a factor of millions. This enabled the use of the many now available low-cost transistors for digital signal processing, and getting away from the so-far used analog electronic circuits.

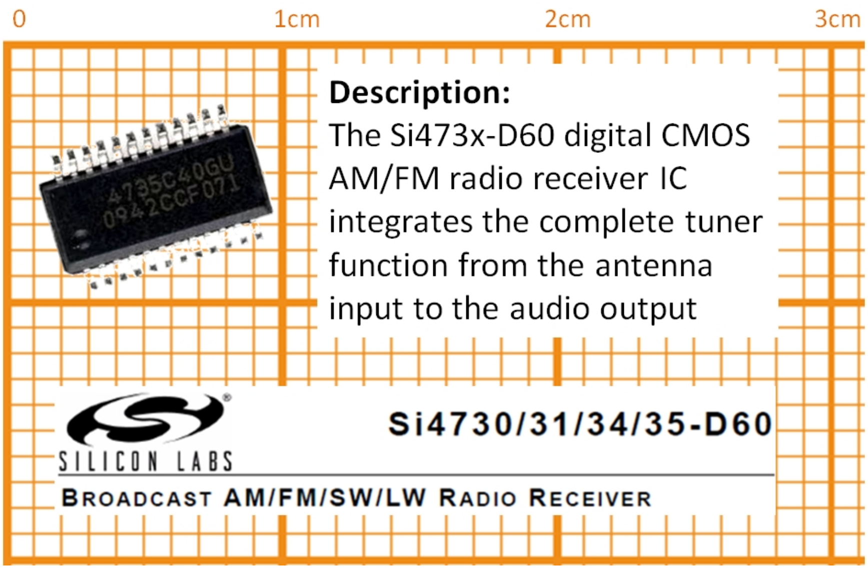


In the example above, the Analog Signal Processing section sketches the conventional, 'real world'

data processing: a time-continuous input signal, here a sine function (sine tone) coming for example from a microphone, is fed into an analog amplifier with an amplification factor of five. This means that the input signal leaves the amplifier five times stronger (louder), and can now be heard through a loudspeaker.
The same process, but now applying digital signal processing, is shown in the lower part: the input signal is now sampled (chopped) in time intervals. Instead of a permanent flow of voltage into the amplifier, we now have a permanent flow of numbers into a computer, representing each the value of the input signal at a given time spot. In our simple example, the computer multiplies each number of this sequence of by 5, and, consequently, a permanent flow of manipulated numbers leaves the computer. The numbers are back-converted into a time signal and can again be heard through a loudspeaker. The clock generator, the heart of any digital system, is triggering the sampling (conversion) of the time signal into a chain of numbers, is triggering the computer and finally also the back-conversion of the train of numbers into time-dependent voltages and currents. This is one of the main differentiators of the digital world compared to analog one.

In a nut shell: in an analog system, the shape of the voltages and currents all over the system correspond to the physical, time-dependent and continuous signal, while in a digital system, the original analog signals are quantized, i.e. represented by their 'values' per time unit. This means that transmission, amplification, modulation etc. of real-world analog signals can now be handled by manipulating numbers, what means, handled by computers. And since a computer is a calculation machine, it can do anything with the numbers, and not only 'just' amplify a signal. This means that a computer chip, replacing the 'classic' analog systems, is much more flexible. Besides amplifying the signal as shown above, the computer could calculate-off (eliminate) unwanted noise, distortions, or could be used to make the transmitted signal sound ‘nicer’, improve the clearness of voices and so on. And, last not least, instead of re-soldering components like in the analog case, just re-program the chip and you get another signal transmission characteristic. Instead of a limited number of electronic components required for analog signal processing, the modern digital signal processing is based on a huge number of transistors, within a single integrated circuit (IC), and nevertheless cheaper to manufacture due to the extreme device size miniaturization within a single production process.

With this in mind, we can now get back to our example of the radio receiver. A complete such receiver can nowadays be bought for a few Euros as an all-in-one, *single-chip* solution, as shown on the left. The packaged chip contains the complete electronic circuitry from the antenna input to the final audio signal for the loudspeakers and their power amplifier stage. Compared to the few tubes of the Grundig radio from above, we now understand that it features a completely different electronic



solution, with thousands of transistors, a supply voltage down to 2V, and -despite the many transistors- with a power consumption of merely 100 milli(!)-Watt compared to the 75 W of the tube solution. The chip itself, inside the package, has a size of only ~3x5mm² instead of the considerable size of the electronic tube radio version of the 1950ies. And the price of a few Euros for this single chip should be compared to the price of the many components in the 1950ies, their hand placement and soldering of altogether several hours work time.

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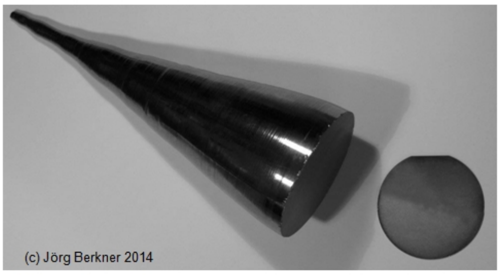
- Today's Electronic Circuits And Their Design

With the technology evolution discussed above, it becomes clear that designing electronic circuits nowadays is completely different to what it has been 50 years ago. A single chip of a few mm², containing transistors with each a diameter down to a few nano meters
(1 nm = 0.000000000001 m, compared to a human hair with about 0.1 mm = 0.0001 m diameter) can not be developed any more by soldering together the individual components (bread boarding).

This leads over to discussing a bit what such a chip is all about.
It's basically a rectangular or quadratic piece of a crystal, and on its top surface we have tiny regions which have been manipulated to act like a resistor, a capacitor, a transistor, a diode etc. These components are interconnected, again on the top of the crystal, by tiny layers of ultra-thin metal lines, typically made from aluminum.

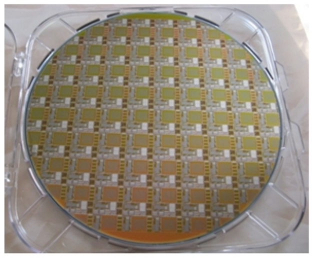
In the pictures below, from the left to the right, we see the most often used base material: raw silicon. After its intensive purification , an ultra-clean mono-crystal with well-defined electrical characteristics is manufactured and cut into thin slices, so-called wafers (~0.5 mm thick, with a diameter of up to 30 cm ~ pizza-size !). The upper side of such wafers is then further processed, so that specific regions act like resistors, others like capacitors, transistors, diodes etc.

raw silicon
(poly crystal)



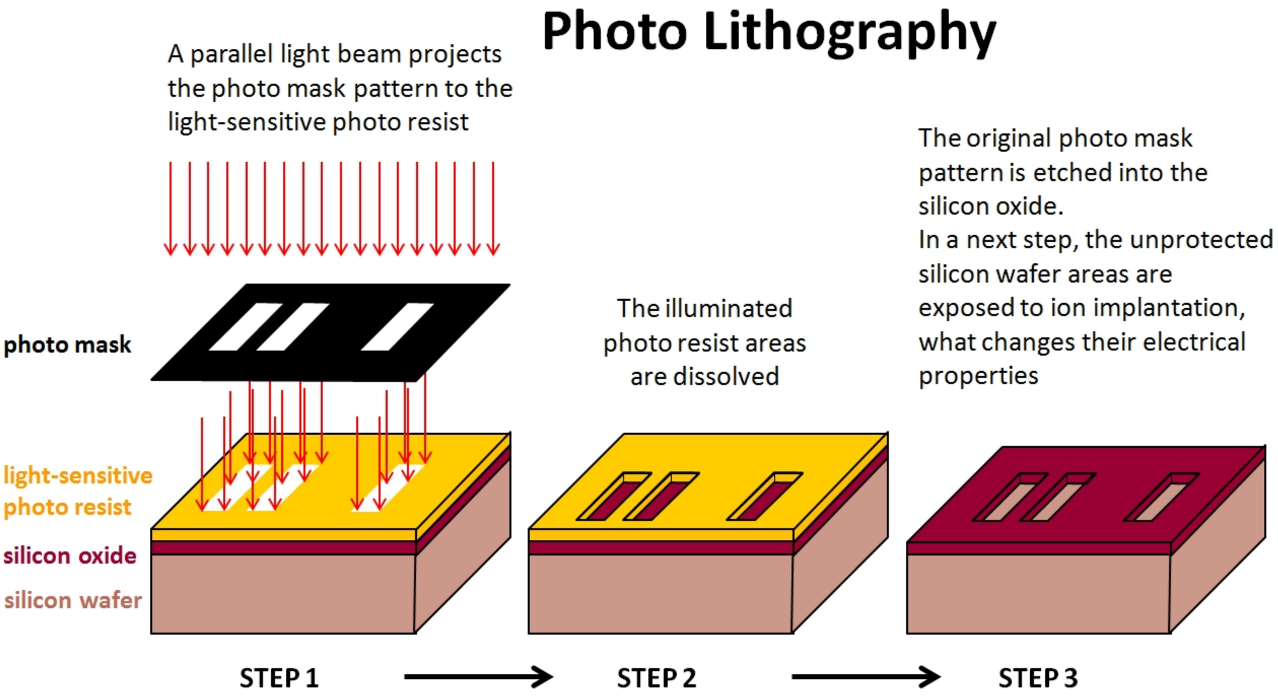
purified silicon
(mono crystal)

silicon slice (wafer)
before component
implantation



silicon slice (wafer) after
component implantation,
with many regions of
identical performance
(chips)

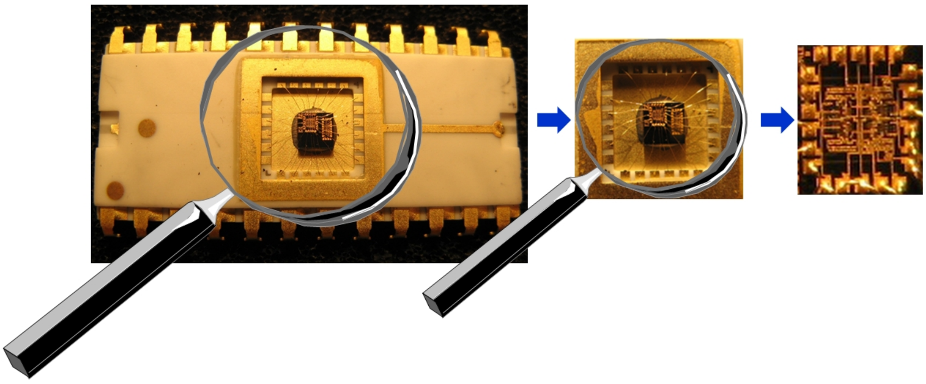
In a pretty simplified view, this component implantation is performed as follows:
First of all, the whole wafer surface is oxidized. Then, a special photo lithography process is applied: a thin layer of photo resist (like with the old analog film material), followed by a light projection of a mask onto the wafer representing the layout of the individual chip production step. Illuminated regions of the photo mask thereby become soft and can be cleaned-off, while unexposed parts stay.



In a next step, etching is applied to etch-away the silicon oxide in the unprotected areas. The remaining oxide areas, representing an exact copy of the previous photo mask, act as a very stable and robust protection shielding for the next step: the manipulation of the electronic properties of specific crystal regions. In this step, radiation or diffusion of ions is applied, to affect or change the physical behavior of the silicon wafer at the non-covered locations. This means, the electronic properties of these locations can be altered to later behave like a transistor, a resistor etc.

This masking and radiation/diffusion process is performed in several layers what corresponds to a vertical growth of regions with specific electronic performance. Finally, by again applying the optical masking technology, metal layers are deposited on top of the manipulated crystal surface, acting as interconnections of the previously manipulated crystal ranges. After these manufacturing steps, the raw silicon slice of the beginning has become a manufactured wafer containing many regions with identical electronic behavior.

The wafer is finally cut into pieces, so-called chips. The chip itself is then mounted inside a package, and the chip contact pads are connected by tiny metal wires to the contact pads of the package, as shown in the photographs below.



This chip fabrication process implies the challenge for today's electronic circuit designers to basically develop photo masks for all the individual chip production steps, corresponding to the desired electronic chip performance, which lead to a fabrication with correct electrical behavior as designed/expected. And this performance should be achieved right-the-first-time, because corrections or changes in the electronic circuit due to malfunction of the first chip production are simply not possible. They would require a complete new manufacturing process, what would cost an enormous amount of money.

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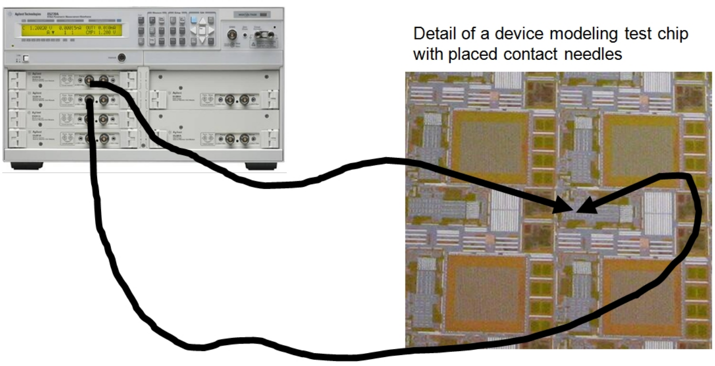
- Electronic Device Modeling

So, after all, what is a Device Modeling Engineer, what is his/her task and why is it important ?

For modern electronic chips, i.e. integrated circuits, there is no way to repair design errors. Once a chip has been fabricated, it has to fulfill its electronic specifications, or the whole design has to be thrown away. Therefore, the electronic circuit design engineer needs to know in advance the electric characteristics of each component he/she wants to apply in the chip design. This means, for every component used, a mathematical model of its electronic performance is required, valid for all kinds of operation conditions.

Therefore, electronic device modeling engineers design special chips, which do *not* contain complete electronic systems (like a radio receiver), but instead, contain *individual* electronic devices like transistors, diodes, resistors, capacitors etc., which can be contacted *individually*, as shown below.



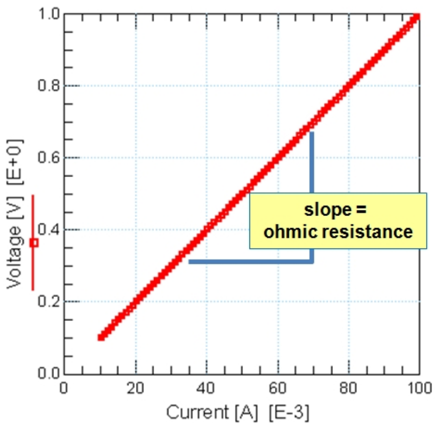
Many different measurements are performed on these devices, in order to get a full picture of their behavior under all kinds of operation modes used later in the chip design. The measurement results are stored on computers, resulting in a large set of characterizing data files. In a next step, mathematical equations are fitted to the measurement data. Instead of the many measurement data, the modeling engineer ends up with providing the modeling formulas and their parameters, usually called device model parameters, to the chip designer.

Let's consider the case of a resistor, and its standard DC characteristic (no frequency dependence). For its characterization, the modeling engineer would apply a DC current sweep to the device, and measure the resulting voltage drops. This results in a two-columns sheet of measurement data:

Applied Current[A]	Measured Voltage[V]
0.01	0.1001
0.011	0.1099
0.012	0.1200
0.013	0.1301
...	...
...	...
0.098	0.9799
0.099	0.9900
0.1	1.0001

In order to simplify, and also to generalize the DC measurement result of the resistor, the modeling engineer then selects *an appropriate, standardized mathematical equation*, in order to *model the behavior of this device*. In our example, it is the well-known resistor formula, as shown below. When applying this formula, i.e. the *model*, to the measurement data, we get a quite simple result: a one-parameter DC model of the resistor: R=10 Ohm. This model, V = R * I, with its single model parameter R, now describes this resistor's DC behavior for all current and voltage bias conditions, wherever this resistor is used within the chip design.

Modeling an Ohmic Resistor



Resistor Characteristics Formula:
(*The Model*)

$$\text{Resistance [Ohm]} = \frac{\text{Voltage [Volt]}}{\text{Current [Ampere]}}$$

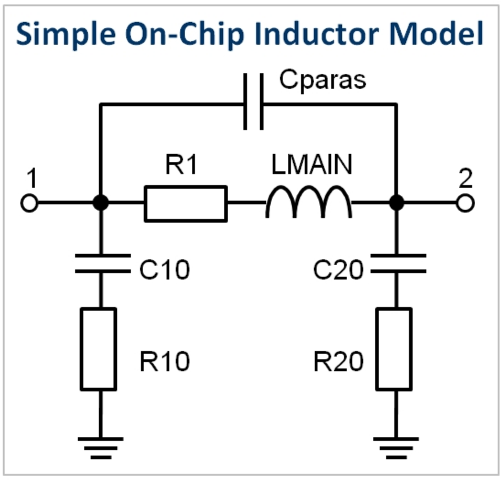
Modeling Measurement Result:
applying 100mA -> 1V

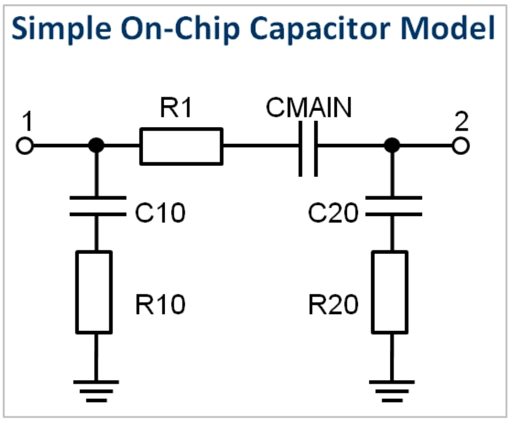
$$\text{Resistance [Ohm]} = \frac{1\text{V}}{100\text{mA}} = 10\,\text{Ohm}$$

In a second step, the modeling engineer would then investigate the frequency (AC) behavior of the resistor: applying a frequency-swept test signal on top of several DC operating points, the frequency-dependence of the ohmic DC resistance would show up, resulting in an improved DC&AC modeling equation for the resistor.

For the characterization of capacitors or inductors, a frequency performance test is performed (impedance measurement), resulting in a model for the capacitor or inductor valid for all operating conditions later in the chip design. Usually, for this modeling task, the modeling engineer would compose a circuit from ideal passive Spice components representing the main component and also its parasitic effects.

For an inductor for example, this would be the main inductance LMAIN representing its ideal performance, plus a series resistor R1 representing the ohmic losses of the inductor, a fine-tuning capacitor Cparas for fitting/modeling the highest frequencies, and also the inevitable on-chip parasitic capacitors (C10, C20) to ground including their losses (R10, R20), as shown below.



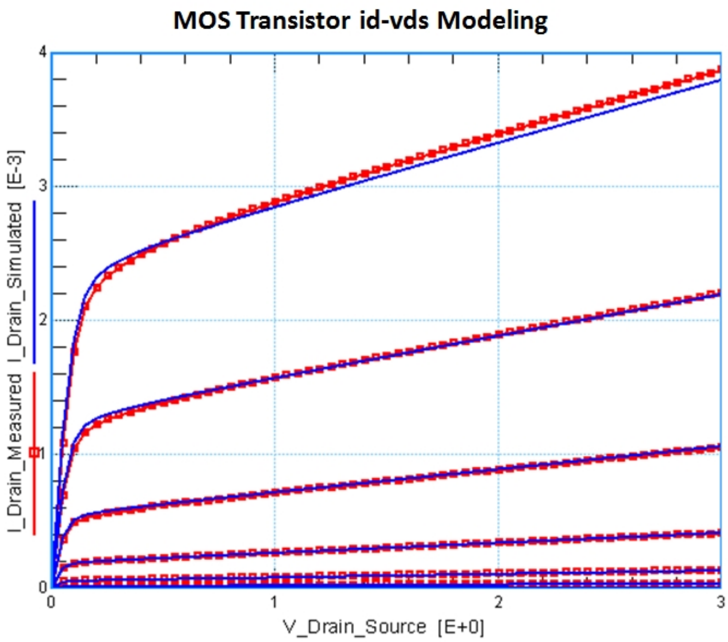


The modeling of non-linear components like diodes or transistors is a bit more complex, but once again, it refers to the same concept as already discussed:

- ✓ first a complete characterization measurement of the device from DC to highest frequencies
- ✓ then an accurate verification of the measurement results
- ✓ followed by fitting mathematical formulas to the measurement data
- ✓ resulting in a device description by the formulas and their parameters.

An example of such a mathematical MOS DC transistor model (blue), fitted to the real measurements of a transistor (red), is shown on the right. It represents the dependence of the transistor's output current (I_Drain) as a function of the input voltage (V_Gate_Source) and the output voltage (V_Drain_Source).

The measurement data are in red, the fitted formula performance (the model) in blue.



As a remark about the requirements for transistor device modeling, and coming back to the discussion of analog and digital circuits, digital chips are based on handling quite simple signals. Since numbers in computers are not expressed in the well-known 'human' decimal system (numbering from 0 to 9), but rather in a numbering system with only two values, 0 and 1, the transistor model for digital application is rather related to describe its time-domain performance: the speed of transiting from low voltage (number '0') to high voltage (number '1'), its delay and its over/undershoot (ringing) is the main device modeling aspect. On the other hand, transistor models for analog applications, i.e. the interface between the digital computing part of the chip and the human environment, but also the transmission of digital signals by antennas from a sender to a receiver (e.g. mobile phones) through the 'real-world' atmosphere, are based on fitting the measurements in both the DC, and also the linear or non-linear frequency domain.

After all, the modeling result (equations and parameters) of each electronic chip component is combined with the chip production information (mask layouts for each production step), what gives the so-called design kit. And this design kit is then used by the chip design engineer in his/her computer-based design tool, enabling a successful right-the-first-time production of the desired chip.

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Conclusions

Due to the impossibility to repair manufactured chips, the accurate modeling of electronic devices, i.e. the characterization of the device performance by mathematical formula and their fitting parameters, is a mandatory task for successful chip designs. Or, in other words,

→ Without good models, based on verified, accurate measurements, no good chips ←