

Switching Circuits and Logic Design
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Lecture - 10
Emerging Technologies (Part 2)

So, we continue with our discussion on some Emerging Technologies for implementing logic gates. So, we talked about all optical implementations in the last lecture.

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Memristor: An Emerging Technology

- In 1971, Leon Chua predicted the existence of a fourth fundamental passive circuit element called Memristor.
 - Memristor = **Memory** + **Resistor**
 - Resistance value changes in response to applied voltage.
 - Can memorize its last resistance value even when the voltage is withdrawn.

The diagram shows four fundamental circuit elements in hexagonal boxes: Voltage (v), Current (i), Charge (q), and Flux (Φ). They are interconnected as follows:

- Resistor**: Voltage (v) and Current (i) are connected by the equation $v = Ri$.
- Capacitor**: Voltage (v) and Charge (q) are connected by the equation $q = Cv$.
- Inductor**: Current (i) and Flux (Φ) are connected by the equation $\Phi = Li$.
- Memristor**: Charge (q) and Flux (Φ) are connected by the equation $\Phi = Mq$. The Memristor is highlighted in a red circle.
- Cross-relationships**:
 - Voltage (v) and Flux (Φ) are connected by $v = d\Phi/dt$.
 - Current (i) and Charge (q) are connected by $i = dq/dt$.

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In this lecture which is the second part of emerging technology. We shall be talking about a very interesting technology called memristors. Memristor is actually a combination of the 2 terms memory and resistor, let us try to understand what memristor is.

Well the presence of memristor was first predicted in 1971 by a Professor Leon Chua who considered this device as the fourth fundamental circuit element passive circuit element. Now you know that we have some fundamental circuit element that we know about resistor, capacitor and inductor. And also if you look at the relationship voltage and current are related by $v = Ri$, voltage and charge are related by $q = Cv$, these are well known equation we have studied in schools right current and flux are related by $\Phi = Li$ and also cross relationship is also there $v = d\Phi/dt$ is nothing but the voltage and $i = dq/dt$ rate of change of charge is the current.

Now you see we live in a world where symmetry is seen everywhere. So, Chua's first argument was that something is missing, there is a missing link then he theoretically postulated that there should be another such fundamental circuit element that should connect flux and charge. So, this $\phi = Mq$ this was the relationship that this new device should exhibit and this new device he gave the name memristor. But forgetting his theory behind it, essentially speaking a memristor is a device whose resistance changes in response to an applied voltage, not only that it can memorize the last resistance value even when we switch off the power we withdraw the voltage this is a very interesting property let us see.

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How Memristor Works?

- In 2008, a team at HP Labs successfully fabricated a memristor.
- They used a material with two regions between two platinum electrodes.
 - A region of TiO_{2-x} (e.g. Ti_4O_7) with free oxygen vacancies. (**Low Resistance**)
 - A region of pure TiO_2 . this region is highly resistive. (**High Resistance**)
- The boundary between the two regions moves in response to the voltage applied across the device.

The diagram illustrates the physical structure of a memristor. It consists of two platinum (Pt) electrodes on the left and right. Between them are two regions of titanium oxide: a left region of TiO_{2-x} (low resistance) and a right region of TiO_2 (high resistance). A blue arrow indicates the movement of the boundary between these two regions. The overall length of the device is labeled as 10-12 nm, and the cross-sectional area of the electrodes is labeled as 3 nm x 3 nm. A small inset shows a circuit symbol for a memristor with a resistor symbol and a capacitor symbol inside a square.

Very briefly speak you see Leon Chua predicted the presence of memristor in 1971, but it was much later in 2008. So, it is about 37 years later means a team from the HP lab USA, they fabricated a device they did not know what the device was, but they saw that it is exhibiting some very peculiar properties, later on they looked at the paper by Chua and they saw that well the properties are very closely matching with what Chua had predicted. So, they accidentally they fabricated a memristor. So, how did they fabricate the device?

They used a material like here shown in the figure, they created a device where on one side there was a region of pure titanium dioxide and there was a other side this is also an oxide of titanium, but with some oxygen vacancy, this is called oxygen vacancy because

in TiO_2 the number of oxygen atoms is double that of titanium, but you see it is TiO_2 minus x sum. So, so one such oxide is Ti_4O_7 something like this was put here and on the both side for connection they used platinum. So, in this device what they found the size of the device is very small cross section area was as small as 9 nanometer square and the length was 10 to 12 nanometers.

Now, they observed symbolically they represented this device like this, this is actually proposed by Chua this side where there is this oxygen vacancy, this part is solidified and this symbol is like this. This is a symbol of a memristor. So, the idea was that if I apply a positive voltage on this side and a negative voltage on this side, then what will happen? This boundary will be moving to the right because oxygen vacancies are positively charged they will be repelled by this positive they will be moving right and this is a region of low resistance and this is a region of high resistance. So, the low resistance region will be expanding the overall resistance will decrease.

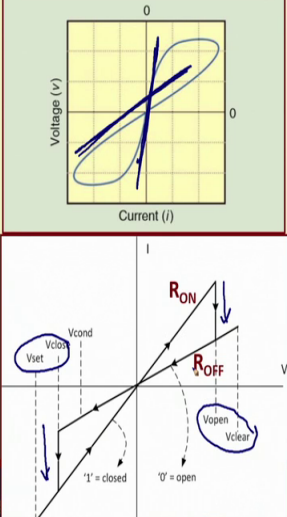
But if I apply a reverse voltage, then the boundary will be moving towards this direction. So, this oxide region will be shrinking and the titanium dioxide region will be expanding. So, the overall resistance will be increasing. So, just by applying a voltage of a suitable polarity, I can either reduce the voltage or increase the voltage. Now another interesting property was that this oxygen vacancies has a very unique property that if you withdraw, the voltage they will remain in the position they were the last point in time.

So, they will not change, which means the change in resistance that has taken place is nonvolatile in nature what is meant by non volatile? A some change is said to be non volatile, if it remains even when I have withdrawn the voltage or the power supply. Here it is something like that, I can change the resistance by applying a suitable voltage then if I withdraw the voltage, the old resistance value will remain the device will be remembering the resistance. So, you can understand that I can implement a very simple memory device using this; it can memorize the resistance right.

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Resistance Switching in Memristors

- The voltage-current characteristics exhibit a pinched hysteresis loop.
- Two distinct resistive regions exist on the curve (R_{ON} and R_{OFF}).
- Possible to switch from R_{ON} to R_{OFF} or from R_{OFF} and R_{ON} by applying a suitable voltage.
- This property makes it useful for storage as well as logic design applications.



The slide features two graphs. The top graph is a plot of Voltage (V) versus Current (I) showing a pinched hysteresis loop. The bottom graph is a V-I plot with two linear regions: a steeper one labeled R_{ON} and a shallower one labeled R_{OFF} . It also shows switching voltages V_{set} , V_{clear} , V_{close} , and V_{open} , and states '1' = closed and '0' = open.

So, very briefly let us talk about the characteristics of such a device, this has been quite widely studied by many researcher voltage and current characteristics exhibits this kind of behavior it is called a pinched hysteresis loop there are 2 region you can see one here and one here.

So, this can be approximate by a curve like this, one with a low resistance. So, see this is voltage and current. So, higher slope means low resistance or this is current here voltage reverse and this will be R_{OFF} is high resistance, because this current voltage slope means current is smaller resistance is higher. So, there are 2 distinct resistive regions low resistance and high resistance and I can switch from one resistance to the other by applying a suitable voltage. If I apply a voltage V_{open} or any voltage beyond that let us have V_{clear} , then it will switch from R_{ON} to R_{OFF} . R_{ON} to R_{OFF} , but if I apply a voltage negative voltage beyond V_{close} , then it will switch from R_{OFF} to R_{ON} . So, I can switch from low resistance to high resistance or high resistance to low resistance by applying a voltage of suitable polarity.

Now, this property that a memristor can remember the last resistance value, it makes it very useful for implementing memory devices storage and we shall see it can also be used for implementing some gates logic gates logic design. So, we shall very briefly look at this technology.

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Some Properties of Memristors

- Very small in size. ✓
- Very low power consumption, and non-volatile property. ✓
- Can be laid out on a crossbar structure in a very compact way.
- Applications:
 - Implementing non-volatile memory systems (Resistive RAM).
 - Modeling neural networks / neuromorphic computing.
 - Implementing digital circuits.
 - Allows a new computing paradigm called *in-memory computing* (both memory and processing carried out in the same hardware unit).

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So, we had already said memristor is something which is very small in size much smaller than the current CMOS transistors.

Well, it consumes a little power only during operation, but when you are not means operating you can withdraw the power. So, there is very low power consumption it can remember the last resistance non volatile. Cross bar structure means you can have a compact implementation some rows and columns. These are 2 different rows and you can connect the memristor between rows and columns like this very conveniently etcetera this is called a cross bar structure some of the application just to name one is we can use this to implement memory systems nonvolatile memory systems. This is called resistive random access memory resistive random access memory resistive.

We can model brains there is also some work where some neural networks or some neurons were implemented using memristors and of course, we can implement gates some digital circuits ok. So, we are not going into the detail of this because this is slightly beyond the scope of discussion here, I just wanted to name a few application.

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Implementing Logic Gates using Memristors

- **Memristor Aided Logic (MAGIC) design style**
 - We can implement all basic gates like AND, OR, NOT, NAND and NOR.
 - Stateful design style :: inputs are not applied as voltages, but as resistive states in memristors (High resistance – 0, Low resistance – 1).
 - As a matter of convention, the memristor representing the gate output must be initialized before the computation.
 - AND, OR : initialized to 0.
 - NOT, NAND, NOR : initialized to 1.
 - A voltage V_o of appropriate magnitude is applied for gate evaluation; V_o must be large enough to enable the output memristor to switch state when required.

(Hand-drawn diagram of an AND gate symbol with two input lines and one output line, with checkmarks next to it.)

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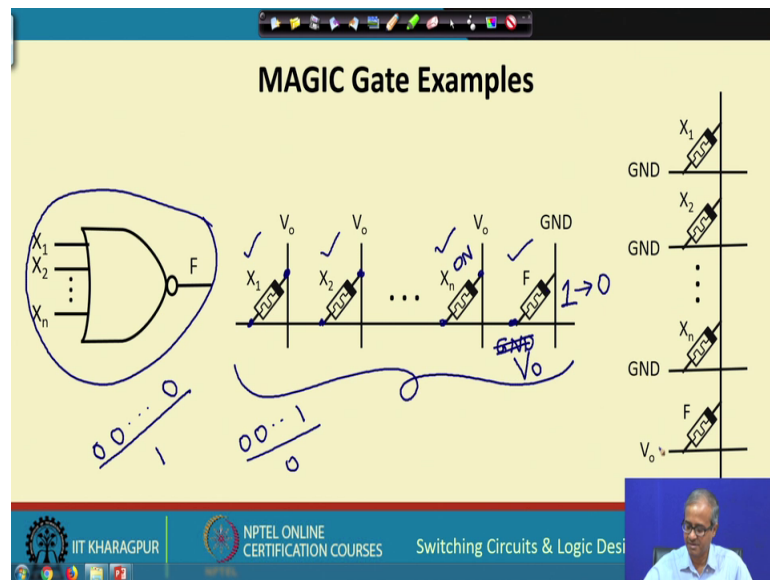
Now, let us briefly look at how we can implement logic gates is a minister without going into much detail. We shall be talking about 2 broad techniques one is called memristor aided logic in short magic. Now using magic you can implement any of the gates AND OR NOT NAND NOR and in this method you see for a conventional gate when you had implemented using TTL or CMOS this inputs we were applying as voltages and the output we were getting as voltage.

But for circuit using memristor it is different, we call it stateful design style where we apply the inputs not as not as voltages, but as resistive states of the memristor the meaning is something like this, suppose I am implementing a gate with 2 inputs there will be 2 input memristors by applying a suitable voltage, I shall be initializing those memristor to either the high resistance or the low resistance states right. If it is high resistance I call it logic 0 if it is low resistance I call it logic 1.

So, the inputs I am not applying as voltages, but I am applying as resistance values in the memristors this is called stateful logic ok.

So, this is the convention and in memory stated logic, when you carry out a gate operation you have to initialize another memristor, where the output will be stored. So, we initialize it to either 0 or 1 depending on the type of the gate and some voltage has to be applied on the input site to evaluate the gate, I just show you how this circuit looks like.

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Here I have just taken an example of a NOR gate, this is an n input NOR gate there are n number of inputs and one output. Now you can very easily implement it using memristor like this, there are a number of memristors x_1, x_2 to x_n which represent the inputs and one memristor representing the output and the previous slide we mentioned for NOR gate this output memristor must be initialized to the one state which means on and depending on the inputs we will have to initialize these input memristor.

Suppose the inputs are all zeros because it is a NOR gate when the inputs are all zeros the output has to be 1; if the inputs are all zeros means what these are all high resistances. So, this V_0 is connected to this point V_0 is connected here, because this is a high resistance very little current will be flowing and these are all connected on this side and because this high resistance no current will be flowing and this point is grounded and this point will be approximately at the ground potential ground. So, on the output memristor there will be no current flowing and it was one it will remain as one. So, it remains as one.

But let us say at least one of the input is that 1 let us say the last input is 1. So, for a NOR gate the output should be 0 let us see how it happens. Let us say one of them is one may this x_n let us say this is on; this is the on means V_0 will be connected through this is a low resistance and this will not be ground, this will now be V_0 . And this V_0 will be applied across this memristor see this part is ground, this point is V_0 . So, you are

applying a higher voltage on the other side and a lower voltage, on that ti 4 or 7 side. So, this will be reversed biased and the output will be changing to 0 to off. So, this is how it works.

Now, not only like this you can also connect it like this in a different way, where of course, the connections will be different, but I have just shown this to you just for your convenience ok. This is one way you can implement some gates using memristors just to give you an idea.

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IMPLY function implementation using memristors

- Material Implication function: $A \rightarrow B = (A' + B)$
- Can be implemented using two memristors and one resistor.
- The inputs are applied by initializing the resistive states of the two memristors.
- The output gets stores as resistive state in the second memristor.
- The IMPLY function along with constant 0 is functionally complete.
 - We can realize any basic gate, and hence any arbitrary function.

Handwritten notes: $B=0$, A' ✓, $A' \rightarrow B$, $A+B$ ✓

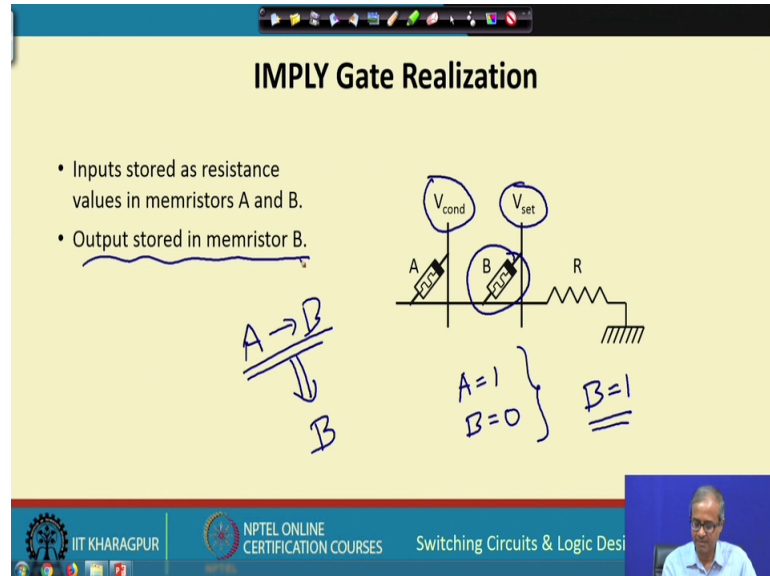
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And there is another kind of a logic design style which is also quite widely explored, this is called imply function. An imply function is defined like this you take the not of a variable A and then do a or this is defined as imply function. Now using memristor you can very easily implement imply function also. Now, it can be shown that imply function along with constant 0 is again functionally complete. Like for example, if B equal to 0, if B equal to 0 then you can implement what A bar or 0 means it will be A bar; that means, you can implement not operation.

So, since you can implement not operation then you can just apply the input A was that, you apply A bar and then imply B, this will become A or B which is or operation. So, so you can implement a not, you can implement an or this again is a functionally complete set as we shall see later. So, you can realize any arbitrary function also using imply. So,

here I am not going into detail, just to give you a basic idea that this memristor is a very promising technology and you can use it for designing logic also.

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The slide, titled "IMPLY Gate Realization", contains the following content:

- Inputs stored as resistance values in memristors A and B.
- Output stored in memristor B.

Handwritten annotations on the slide include:

- A logic diagram showing $A \rightarrow B$ with an arrow pointing to B .
- A circuit diagram with two memristors, A and B, and a resistor R connected to ground. Memristor A is labeled with V_{cond} and memristor B with V_{set} .
- Handwritten values: $A=1$, $B=0$, and $B=1$.

The slide footer includes the IIT KHARAGPUR logo, NPTEL ONLINE CERTIFICATION COURSES, and the course title "Switching Circuits & Logic Design". A small video inset shows a man in a light blue shirt.

And imply gate can be realized like this 2 memristors and one register, the convention is that the input should be stored in A and B and after operation the output; that means, now this A implies B this will be the output, this value will get stored in B.

So, the value in B will be overwritten. So, again the voltage we are applying here is V_{cond} and V_{set} , I am not going into the detail here. So, the basic concept is like this that you have a circuit comprising of 2 memristors and one register. So, whenever you want to carry out some logic operation for some given value of A and B let us say A equal to 1 and B equal to 0, then you will have to initialize the values of A and B appropriately.

Let us say I initialized A to 1 I initialized B to off, then I apply V_{cond} and V_{set} then this $A \bar{B}$ or B will be 1. So, what will happen is that after computation B will become 1 this will be the output because output will also be stored in memristor right. So, actually this is how the imply gate works. So, I here in this lecture we have given a very brief idea without going to the detail regarding how this emerging technology memristor works. So, if some of you are interested to know more about memristors, you can read the literature if you do a Google search you will get lot of material about memristors a lot of interesting applications that people are talking about.

So, a few things people are predicting that the first kind of application of memristor that you will see in the market will be some non volatile memory devices like your the pen drives, USB drives that we use today. They will be of much higher capacity much faster as compared to the present day USB drives. So, let us hope that we get to see such devices in the market very soon in the near future.

So, with this we come to the end of this lecture, now from the next lecture onwards we shall be starting our discussion on so called switching functions and switching expressions, how do we represent such functions, how do you manipulate, how do you minimize. And later on we shall see how do we implement them using gates and various other circuit modules, digital circuit modules to implement the desired functionality. So, we shall be starting this discussion from the next lecture.

Thank you.