Fundamentals of Micro and Nanofabrication

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Lecture – 04
Introduction to cleanroom

Hello. This is a course on Fundamentals of Micro and Nanofabrication, my name is Sushobhan Avasthi, I am from the Indian Institute of Science and let us get started. This lecture is on the cleaning of substrates. In the last lecture, we looked at what are the various substrates that we have on offer and what are the various properties they have. In this lecture, we will try to go one step further and start seeing how to do fabrication on it, and most of the fabrication starts with a cleaning step, so, that is the subject of this lecture.

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Agenda

- Commercial foundry or Fabs
- Importance of cleanroom
  - – Particulate contamination
  - – Chemical contamination
  - – ITRS requirements
- Process
  - – Wet
  - – Dry
  - – BEOL
- Characterization

Agenda: we will start with some description of what a commercial foundry or fab as it’s called looks like; that has a bearing on why we need so much cleaning. Only when you understand how the fab is structured, you can appreciate to what level the semiconductor industry has gone to ensure cleanliness and purity.

Then, we will look at specifically two types of contamination, particulate and chemical. Then, we will discuss the ITRS requirements. ITRS is an industry body that gives out the road map of how the industry would be in the future (say in 5-10 years). Looking at the

ITRS requirement, you can appreciate how stringent the cleanliness requirements are. Next, we will talk about the recipes that we use to do the cleaning; we look at some wet recipes, we look at some dry recipes and some back end of the line (BEOL) cleaning. Finally, we look at some characterizations. I will touch on it very briefly because the major thrust of this lecture and in this course is on the fabrication.

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INTEL & MIRCON 25 nm Flash Production Facility (2011)

https://pcper.com/2010/02/an-inside-look-at-intel-and-micron-25nm-flash-memory-production/2/

Cost ≈$10 billon = ₹ 63000 Cr

So, let us start with an example. This is a fab that was jointly made by Intel and Micron, which are two very large semiconductor industries and they set up a joint facility in Utah, sometimes in 2011 for 25 nm node. The rest of the details do not matter but concentrate on this figure that they released describing what the architecture of their cleanroom looks like.

The main cleanroom is where most of the instruments are stored, the wafers are being processed, and the humans interact with the wafers. This is the business end, but behind this business end, is a much larger substructure of utilities that help make this clean room work. Let us take it one step at a time. First, look at the pressurized plenum. The cleanroom remains clean by pushing pressurized air through it. That pressurize air is pushed from this plenum and in order to make sure the air goes from top to bottom, the plenum tends to be at a higher pressure than the atmosphere. This higher pressure is maintained MAH or air handling units that are very high capacity fans that push air, and that air is then pushed down into the room.

The blue things that you see on the top are HEPA filters; these are very high quality, very high fidelity filters that clean this air into the standard that is required for the cleanroom. We will talk about specifics a little later. All of this air that has been purified is very expensive, so, it’s not thrown away but sucked out by these holes in the floor into this clean subfab. The air is then taken back to the MAH and again pushed back and this air circulation is done several times a minute. For example, in the cleanroom at IISc, this air circulation is done 4 times a minute.

This continuous circulation is important for purity and also for safety. End of the day, in a confined space, people need oxygen and that oxygen is to be continuously supplied. So, the circulation also ensures that you never have an accumulation of carbon dioxide etcetera, but those of you who are paying attention may notice that in a closed-loop system ultimately the oxygen will deplete. We cannot have that. MAH also leaves in the fresh air every now and then at a certain rate so that this air is never old or stale. Some part of this air is lost through hoods and other equipment, so, the whole system is designed in a manner that the input air that you are sucking in from outside and the air that you are losing from the cleanroom are balanced and a certain pressure is always maintained inside this cleanroom.

Finally, there is the utility level. A lot of what we just talked about requires large machinery, air handling units, air conditioners purifiers etcetera and the cleanroom itself has a lot of equipment that require pumps, cooling water, chilled water, compressor etcetera. All of those utilities are supplied from the bottom. This whole design also serves a functional purpose - the cleanroom is a very expensive and productive space. So, every time something goes down, you do not want to shutdown the cleanroom. You just take the defective equipment into the clean subfab, do whatever maintenance – repair you want to do and then push back up.

All of this air handling the architecture comes at a significant cost. The typical cost of a modern fab is in the order of 10 billion, give or take, which translates to around 70,000 crore rupees. That is a significant investment. When you buy a cell phone that is relatively cheap, you do not really appreciate that behind that cell phone and behind that chip that is cheap, is significant infrastructure investment.

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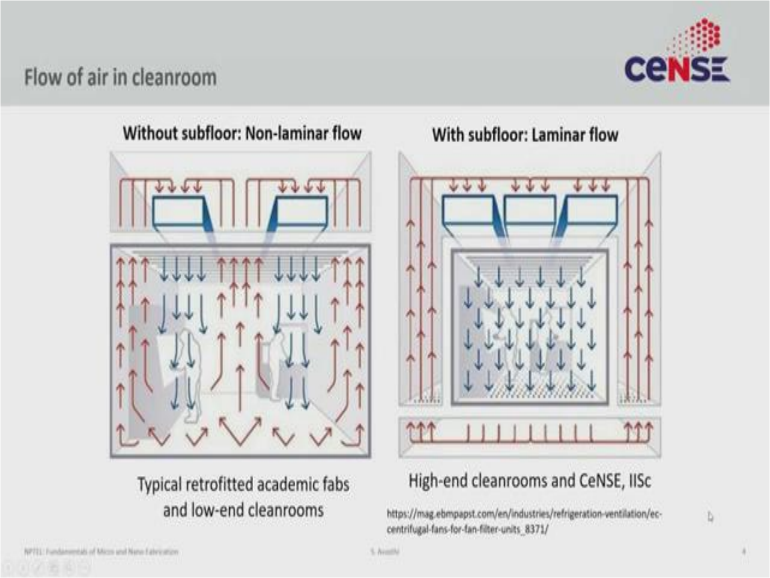

Flow of air in cleanroom

Typical retrofitted academic fabs and low-end cleanrooms

High-end cleanrooms and CeNSE, IISc

https://mag.ebmpapst.com/en/industries/refrigeration-ventilation/ec-centrifugal-fans-for-fan-filter-units_8371/

Let us come to the concept of a cleanroom. The way a cleanroom is maintained clean is by pushing compressed air. Here is a zoomed-in version of what we just saw. Air handling units push the air through these filters into the room that has a perforated floor. That air is sucked out and circulated back in. Any dust that is created either by an individual inside the cleanroom or by the equipment is pushed down by the flow of air. More laminar this airflow is, better the quality of a cleanroom is. On the left is an example of a cheap clean room where the airflow is not necessarily laminar. Typically research fabs or low-cost university fabs tend to be of this design, but high-quality fabs always have a laminar flow (as shown on the right).

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These are pictures of a typical fab, in fact from the same Intel micron joint facility that we talked about. Notice that there are very few people inside and that is by design. The biggest contaminant in a cleanroom is the human inside, so, by reducing the number of humans inside you can get control over the contamination inside.

The second thing you would notice is all the humans are within bunny suits; these bunny suits prevent the particles that you continuously generate from shedding out. These rails on the top are robots that manage the wafers. Humans in modern fabs humans do not come into contact with wafers because we create a lot of contamination.

These wafer wafers are always handled by these robots called Automatic Material Handling System or AMHS. On the left-hand side, these banks of tools are what is doing the processing. Each of them is probably for a different process. The perforated floor maintains the laminar flow of air that keeps the clean room clean.

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Front Opening Unified Pod (FOUP), i.e. hermetic wafer holder

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Over each tool, these orange-colored boxes store the wafers. Wafers are typically processed in batches of 25 or 50 and each of these boxes stores the wafer. The boxes are completely sealed. Despite this being a clean room, the wafer never sees this clean room but a much purer environment inside this pod. Removal and addition of the wafers into the pod and outside the pod is all managed by robots. These are called foups or front opening unified pod.

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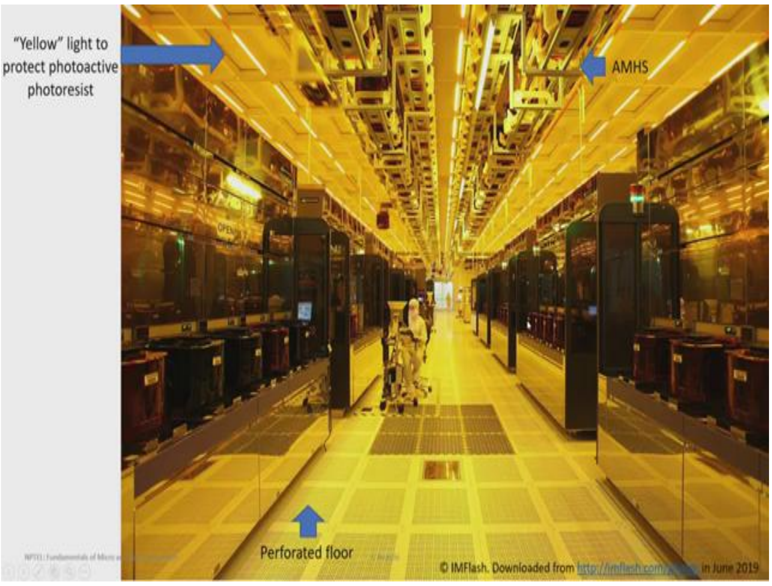

"Yellow" light to protect photoactive photoresist

AMHS

Perforated floor

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This picture is again from the same clean room, but this time you see that there is a yellow light. This yellow light is because when you are doing lithography you have light-sensitive chemicals, that you do not want to be exposed to the blue light. This is some version of a darkroom in the old times when people used to take photography films and develop them in dark rooms. Lithography is a very similar technology that uses similar sort of "yellow rooms", that prevent exposure and allow processing to happen. These tools are lithography tools and the hermetic pods where the wafers are stored. AMHS which are the robots that handle the wafers.

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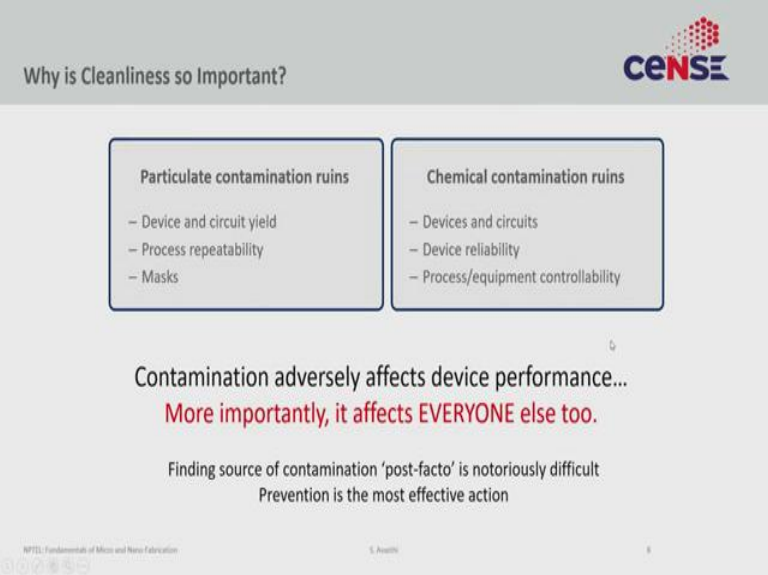

Why is Cleanliness so Important?

Particulate contamination ruins

- Device and circuit yield
- Process repeatability
- Masks

Chemical contamination ruins

- Devices and circuits
- Device reliability
- Process/equipment controllability

Contamination adversely affects device performance…

More importantly, it affects EVERYONE else too.

Finding source of contamination 'post-facto' is notoriously difficult

Prevention is the most effective action

Why do we do so much to prevent contamination in the cleanroom? We spend so, much money behind very highly engineered infrastructure. why is cleanliness so important? The reason is: particulate and chemical contamination, which are the two broad classes of contamination are very bad for the device. Particulate contamination can kill your yield which is the number of the working devices. It can prevent the processes from being repeatable, causing the day to day variation into processes, which is extremely hard to track and does not allow you to do reliable manufacturing. Remember, each chip has billions of transistors and unless all the transistors perform exactly the as designed, you are not going to make a reliable device or a chip.

Chemical contamination causes a whole bunch of reliability problems: chemical might move inside the device overtime changing the performance of the device over time. So, the computer chip that works today may not work 5 years from today. All of those are humongous problems. A lot of cleanrooms are shared facilities where multiple industries or users or research groups work.

Contamination is bad also from a social perspective. It does not just adversely affect your device performance, but contaminating a clean room ensures that everybody’s device performance gets affected. Finding the source of contamination once it has already happened is notoriously difficult. The best way forward is to prevent the contamination from happening in the first place by establishing norms, protocols and keeping the clean room clean.

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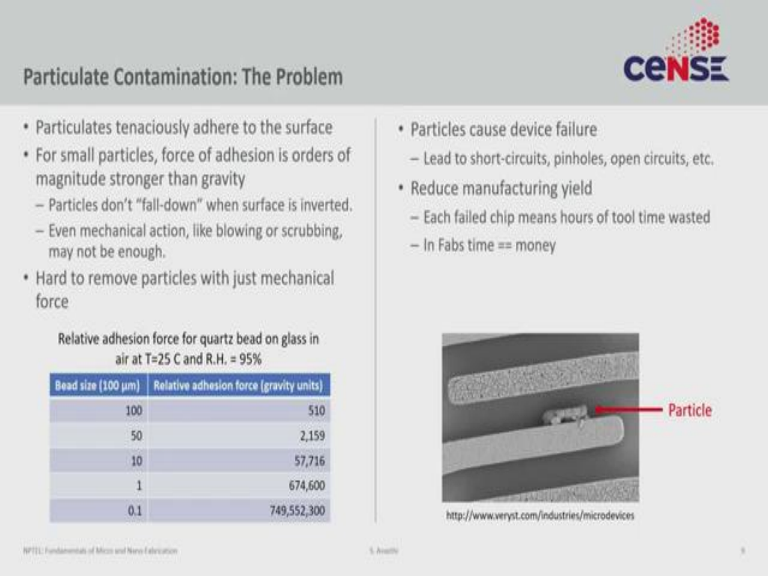

Particulate Contamination: The Problem

- Particulates tenaciously adhere to the surface
- For small particles, force of adhesion is orders of magnitude stronger than gravity
  - Particles don’t “fall-down” when surface is inverted.
  - Even mechanical action, like blowing or scrubbing, may not be enough.
- Hard to remove particles with just mechanical force

Relative adhesion force for quartz bead on glass in air at T=25 C and R.H. = 95%

Bead size (100 µm)	Relative adhesion force (gravity units)
100	510
50	2,159
10	57,716
1	674,600
0.1	749,552,300

- Particles cause device failure
  - Lead to short-circuits, pinholes, open circuits, etc.
- Reduce manufacturing yield
  - Each failed chip means hours of tool time wasted
  - In Fabs time == money

http://www.veryst.com/industries/microdevices

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Let us talk about particulate contamination. At a microscopic scale, this air seemingly transparent and clean has a lot of particles that can then fall on top of the die or a wafer that you are trying to process. And if you are doing micro/nanofabrication, any particle of micro or nanometer scale that falls will ultimately change your device. The problem is exacerbated by the fact these small particles are notoriously hard to remove. Here is the calculation that tries to explain why. Any particle adheres to the surface through some version of a Van der Waals force or surface tension. For its size, that adhesion force is fairly strong. Of course, smaller particles have a smaller force, but that is not an apples-to-apples comparison. A better comparison is how much stronger the adhesive force is compared to gravity (or mass).

For a 100 µm bead, the adhesive force is 510 times stronger, while for a 100 nm bead, the adhesive force is 7.5 million times stronger than the weight. What that means, is particles do not fall down if you take a die and just turn it upside down, the particle will not fall because of gravity as the adhesive force is way stronger than gravity. Even mechanical action like scrubbing or blowing may not be enough to this latch the particle.

Once a particle falls, it is very hard to remove it, especially mechanically and that is why it’s so important to keep the wafer clean by preventing the particles from being inside the cleanroom. Of course, in reality, particles of various sizes are always there. Once particles do form, for example, here is a particle that has fallen between two electrodes, they can change properties, lead to pinholes, shorts or open circuits.

And since the fab is so expensive and the capital investment so large, any loss of time is a loss of money. So, you never want your fab to do wasteful work and it should be productive all the time. Yield needs to be high. Typically yield numbers are ~ 99.9 %.

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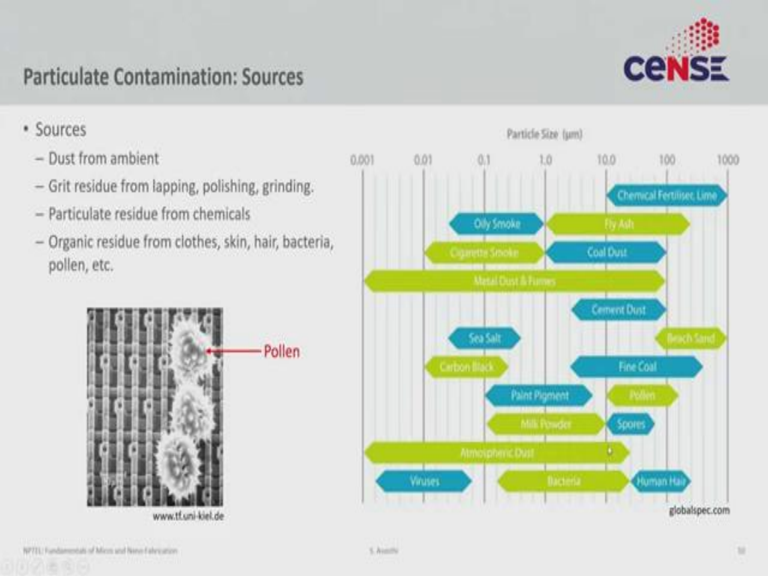

Particulate Contamination: Sources

- Sources
  - Dust from ambient
  - Grit residue from lapping, polishing, grinding.
  - Particulate residue from chemicals
  - Organic residue from clothes, skin, hair, bacteria, pollen, etc.

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What are these various sources of contamination? Here is an example of various types of particles that we can get in ambient air and depending upon what their source is, the size of the particle changes. Clearly the smaller the particle the harder it is to remove. Also, the smaller the particle the more it affects your device performance.

As we are trying to make nano-sized devices, we are more and more sensitive to nano-sized particles. Common examples - pollen, smoke, carbon from burning as well as from natural sources, atmospheric dust, viruses, bacteria; all these things can fall on top of your wafer. Additionally, when you are doing chemical or mechanical processing, just the fact that you are using or touching the wafer would also produce particles. So, those particles also need to be removed.

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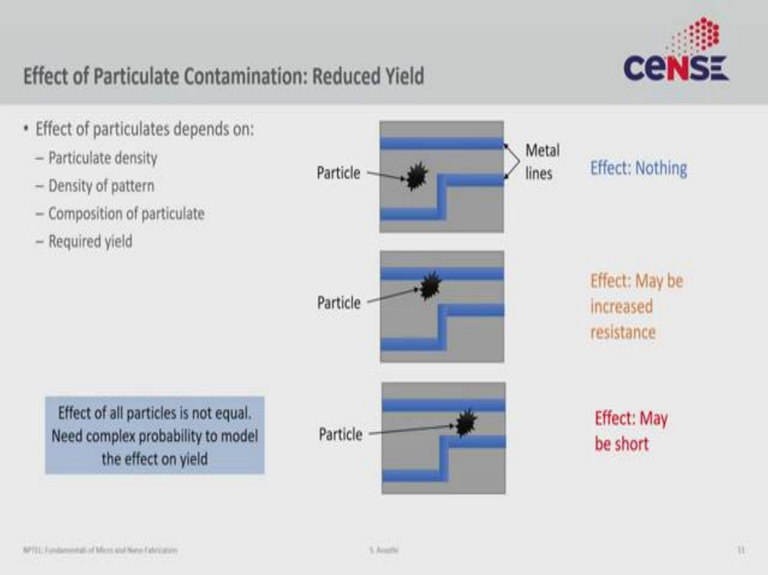

Effect of Particulate Contamination: Reduced Yield

- Effect of particulates depends on:
  - Particulate density
  - Density of pattern
  - Composition of particulate
  - Required yield

Effect: Nothing

Effect: May be increased resistance

Effect: May be short

Effect of all particles is not equal. Need complex probability to model the effect on yield

Particulate contamination problem is a little tricky to model because a fallen particle does not automatically mean that it will cause a problem, it depends on where it has fallen. So, there is a certain amount of probability involved. For example, the particle may have fallen between two metal lines, in which case it is not affecting anything, but if the same particle falls partially on to the line it might increase the resistance, and if it falls between two lines, it might cause a short which may completely kill the device.

So, there is a certain probability associated with the defect doing something really bad. A lot of this leads to fairly complicated mathematics that we will not go into the detail, but I will give you a flavor of what a typical yield calculation would look like.

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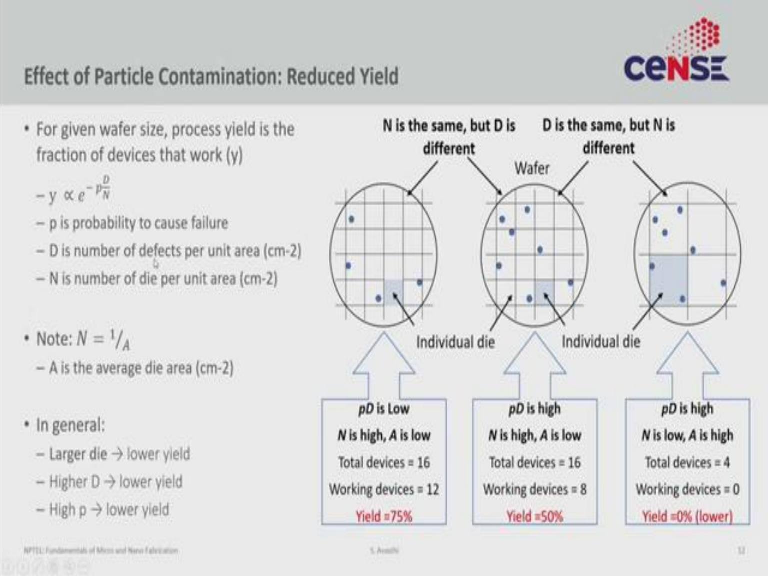

Effect of Particle Contamination: Reduced Yield

- For given wafer size, process yield is the fraction of devices that work (y)
  - $y \propto e^{-p\frac{D}{N}}$
  - p is probability to cause failure
  - D is number of defects per unit area (cm-2)
  - N is number of die per unit area (cm-2)
- Note: $N = {}^{1}/_{A}$
  - A is the average die area (cm-2)
- In general:
  - Larger die → lower yield
  - Higher D → lower yield
  - High p → lower yield

pD is Low
N is high, *A* is low
Total devices = 16
Working devices = 12
Yield =75%

pD is high
N is high, *A* is low
Total devices = 16
Working devices = 8
Yield =50%

pD is high
N is low, *A* is high
Total devices = 4
Working devices = 0
Yield =0% (lower)

Let us start on the left. For a given wafer size, process yield is simply the number of devices or dies that work. In microfabrication, you typically start with a wafer, simultaneously process several dies next to each other and then cut it up so each die is a functional chip that you can sell.

The yield of your process exponentially depends upon the defect density. The more the defect density, the lower the yield. Higher the probability of a defect of causing failure, lower the yield. Yield also depends upon the number of dies per unit area. As an example, let us look at the three figures. You have two wafers (first two) that are roughly the same size. In these wafers each of these blocks is a functional die. After dicing, you get 16 dies each which are a working IC that you can sell.

Now, supposing the same process was done in two different clean rooms; one was very well controlled so, the number of defects was low. These blue dots represent defects that were formed because of particles. There were fewer defects in clean room 1 but more in clean room 2. If you assume that each defect would kill the device, you can easily see that out of the 16 possible working device, on the left you would get 12 working devices, that is 75 % yield and on the right, you would get only 8 working devices, which is the 50 % yield. This is a less productive clean room than clean room 1.

And now this formula probably makes sense to you as far as p into D is concerned. Now in order to understand what this N does, let us look at the third figure. In this case, the wafer is of the same size, however, the die size is different (4 dies instead of 16). Die size is larger and so, A is a little larger. Assume the number of defects to be exactly the same as that on the wafer 2. You can see that none of the dies are defect-free, and the yield is 0. It intuitively makes sense that if you have a possibility of a defect occurring, the smaller the die size the more chance you have of missing that defect, but if your die sizes are large than you do not have any hope of missing the defect and you would always end up with the lower yield. In general, larger dies, higher defect densities and a higher probability of causing a defect would lower the yield. The easiest of them to manage and what is the subject of this lecture is to reduce D; to keep the particle falling onto the wafer to a minimum.

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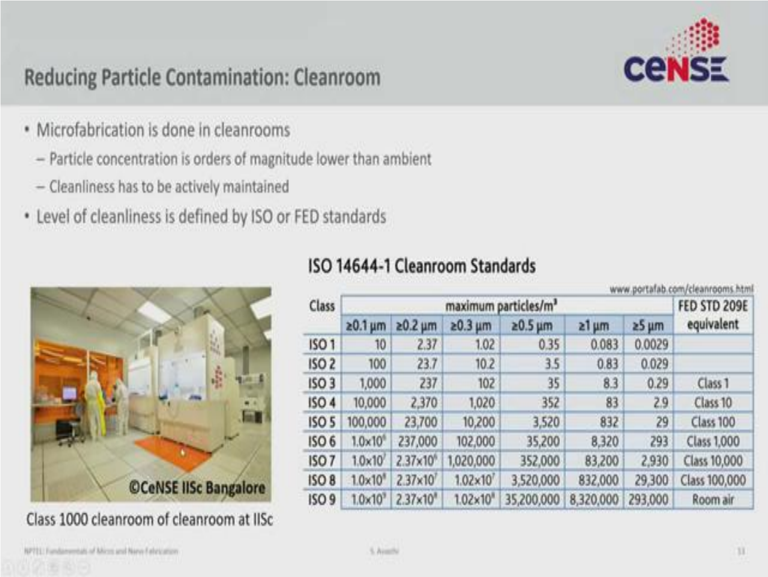

Reducing Particle Contamination: Cleanroom

- Microfabrication is done in cleanrooms
  - Particle concentration is orders of magnitude lower than ambient
  - Cleanliness has to be actively maintained
- Level of cleanliness is defined by ISO or FED standards

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Class 1000 cleanroom of cleanroom at IISc

ISO 14644-1 Cleanroom Standards

www.portafab.com/cleanrooms.html

Class	maximum particles/m^3						FED STD 209E equivalent
	≥0.1 µm	≥0.2 µm	≥0.3 µm	≥0.5 µm	≥1 µm	≥5 µm	
ISO 1	10	2.37	1.02	0.35	0.083	0.0029	
ISO 2	100	23.7	10.2	3.5	0.83	0.029	
ISO 3	1,000	237	102	35	8.3	0.29	Class 1
ISO 4	10,000	2,370	1,020	352	83	2.9	Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29	Class 100
ISO 6	1.0×10^6	237,000	102,000	35,200	8,320	293	Class 1,000
ISO 7	1.0×10^7	2.37×10^6	1,020,000	352,000	83,200	2,930	Class 10,000
ISO 8	1.0×10^8	2.37×10^7	1.02×10^7	3,520,000	832,000	29,300	Class 100,000
ISO 9	1.0×10^9	2.37×10^8	1.02×10^8	35,200,000	8,320,000	293,000	Room air

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How do you reduce this particle contamination? You do the processes in a clean room, where you have a continuous flow of air. There are certain standards (ISO or the FED) for the cleanliness of a cleanroom. You don’t need to remember these numbers. This is a class 1000 cleanroom at IISc. Class 1000 tells you that you should not have more than 293 particles that are larger than 5 µm inside a cubic meter, and it also gives specifications for the particles < 1 µm, < 0.5 µm etcetera. As the particle size becomes lower, you have to tolerate more and more particles because it becomes increasingly harder to clean. Notice that going from a class 100 to a class 1000, there is an order of magnitude change. Going from a class 100 to a class 1, there is two orders of magnitude change and it becomes increasingly hard and expensive to clean. In commercial fabs, the environment that the wafer sees is class 1 or better. It can be ISO 1, and those are very stringent requirements, extremely expensive to maintain. So, this is why the clean rooms are expensive to make and operate.

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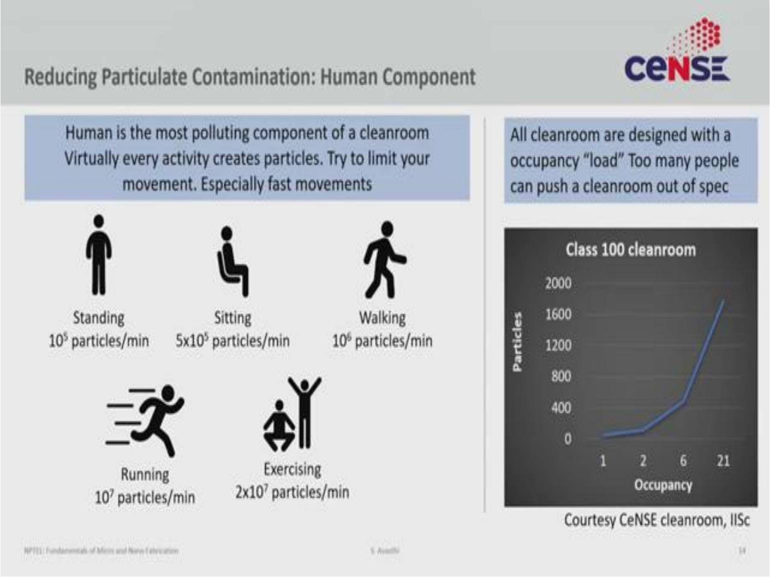

Reducing Particulate Contamination: Human Component

Human is the most polluting component of a cleanroom Virtually every activity creates particles. Try to limit your movement. Especially fast movements

All cleanroom are designed with a occupancy "load" Too many people can push a cleanroom out of spec

Courtesy CeNSE cleanroom, IISc

The greatest contamination inside the cleanroom is human. Every minute you spend inside the cleanroom, you are creating particles. You are shedding hair and skin. Just by talking, little small droplets of saliva come out from your mouth. So, everything you do inside the cleanroom creates particles. And the amount of particles you create actually scales with the intensity of the activity you are doing. If you just standing, you are maybe creating around 10^5 particles, but if you start exercising, you create 10^7 particles.

Inside the cleanroom, you need to be very disciplined. Walk slowly, move slowly, move deliberately you are not supposed to be jerky or hasty. You do your work you get out; do not loiter around because every person inside the cleanroom is a load that it has to manage. This is also obvious from this data that we actually have from IISc clean room. Each cleanroom is designed for a certain number of people inside, so, we expect a certain amount of particles to be created and we design the clean the airflow in the cleanroom to remove those particles at a certain rate. For example, this room has been designed for two people working simultaneously, but if suddenly instead of 2 you have 6 or 21 people inside (say because of training), the cleanroom cannot cope up and the particle count goes up. So, if somebody is doing something critical while there are 21 people inside the cleanroom, they may not get the yield that they need. So, it is very important to keep the discipline of the cleanroom.

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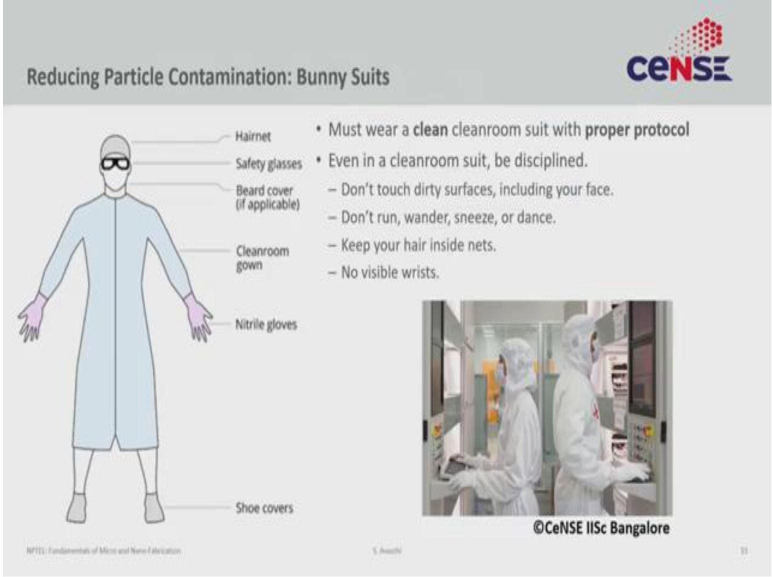

Reducing Particle Contamination: Bunny Suits

- Must wear a **clean** cleanroom suit with **proper protocol**
- Even in a cleanroom suit, be disciplined.
  - Don't touch dirty surfaces, including your face.
  - Don't run, wander, sneeze, or dance.
  - Keep your hair inside nets.
  - No visible wrists.

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One way we reduce (not eliminate) the contamination that humans cause inside the cleanroom is to put you inside bunny suits. Bunny suit typically is a gown made from polyester or fabric that does not create particle on its own. So, it cannot be cotton or a lab coat. You always have gloves, that cannot have cotton or some other lint full fabric. It has to be lint-free, like nitrile gloves. Often hairnet and face masks are required. Glasses are required both for safety as well as protection from particle contamination. If you have a beard, you might also need an additional bear hold. Long hairs are expected to be completely tied so that no hair ever comes out. you also have some shoe covers or booties so that any dust from your shoes or from your feet does not come out.

So, this is what you typically look like inside a cleanroom. A few points to ensure: No visible wrists; you always have to ensure that your glove and the hem of your cleanroom gown come on top of each other so there is no exposed skin. You are not supposed to sneeze, wander, dance or touch any dirty surface which includes your face. Do not wipe your face and work inside the cleanroom because that dirties up the glove which ultimately dirty up the cleanroom.

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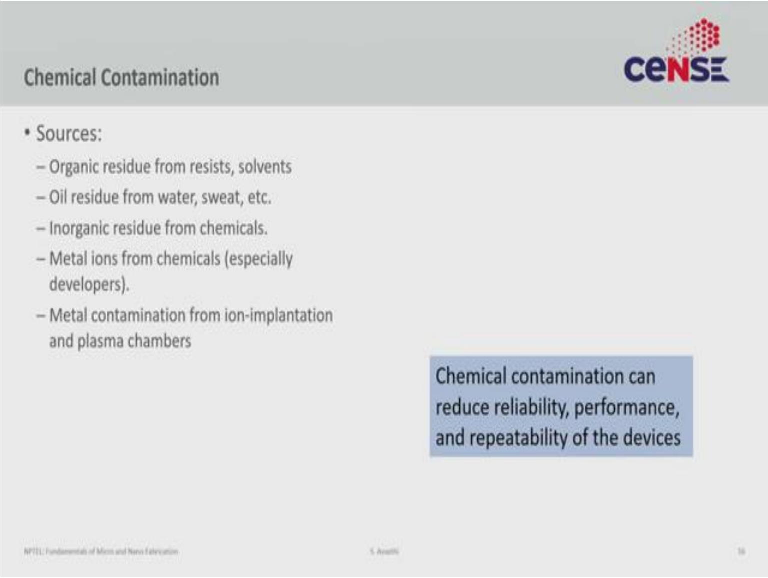

Chemical Contamination

- Sources:
  - Organic residue from resists, solvents
  - Oil residue from water, sweat, etc.
  - Inorganic residue from chemicals.
  - Metal ions from chemicals (especially developers).
  - Metal contamination from ion-implantation and plasma chambers

Chemical contamination can reduce reliability, performance, and repeatability of the devices

The second type of contamination inside a cleanroom: chemical contamination. The sources of chemical contamination can be atmospheric contamination, carbon soot, exhaust from a car that might make its way inside the cleanroom, oil, and sweat from our skin etcetera. A lot of chemicals used inside the cleanroom themselves can be sources of contamination. Some of the tools that we use are made of steel which can cause iron contamination. Iron is a very bad contaminant, at least in silicon. Inside the cleanroom, even if you are doing everything right, you have to actively do things to reduce the contamination that is coming in all the time.

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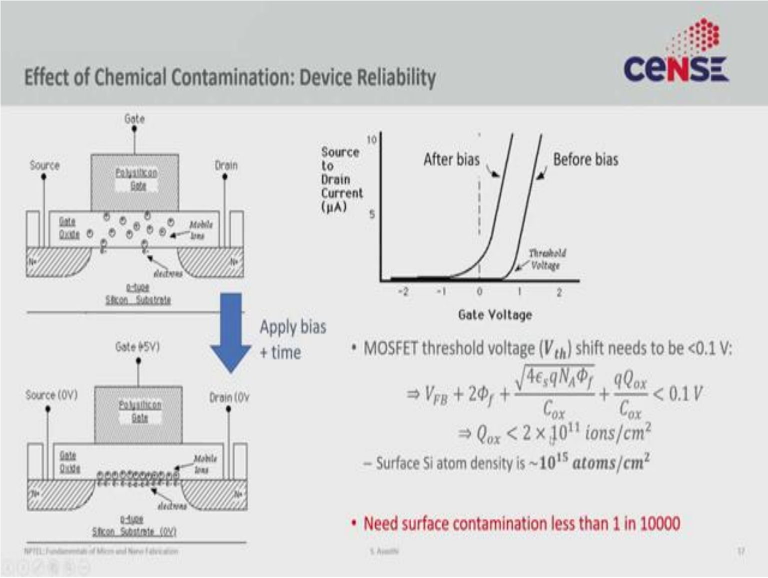

Effect of Chemical Contamination: Device Reliability

- MOSFET threshold voltage (V_{th}) shift needs to be <0.1 V:

$$\Rightarrow V_{FB} + 2\Phi_f + \frac{\sqrt{4\epsilon_s q N_A \Phi_f}}{C_{ox}} + \frac{qQ_{ox}}{C_{ox}} < 0.1\,V$$

$$\Rightarrow Q_{ox} < 2 \times 10^{11}\ ions/cm^2$$

  - Surface Si atom density is $\sim 10^{15}\ atoms/cm^2$

- Need surface contamination less than 1 in 10000

Here is an example of what chemical contamination can do. This device is MOSFET (MOS transistor). The way the MOS transistor works is that there is a sheet of electrons at the interface of the device. That sheet of electrons can be turned on/off by a gate on the top. It is a capacitive coupling. In MOSFET, the electric field (induced by the gate voltage) creates this channel. Supposing you have some sodium chloride contamination from sweat, which means you have positive sodium ions and the positive sodium ions remain in this dielectric. When you apply the gate voltage, these positive charges will move up and down in your gate oxide and shift the current-voltage characteristics of your device.

And this shift cannot be planned for, because it depends on how long you apply the voltage. It is a transient effect, which makes it very hard to design the characteristics and the circuit designers hate it. So, you have to avoid sodium contamination in the first place because once it has happened the devices gone. It does not take much to cause the shift. You don’t need to remember this formula. Let’s calculate the contamination that shifts this I-V characteristic by 100 mV (a relatively small amount). It only takes around 10^{11} ion/cm^2 to cause the change. Compared to silicon surface atomic density (~ 10^{15} atom/cm^2), it is a very small amount. If you have just 10^{11}ion/cm^2, which is 1/10000 contamination, you will shift the I-V by 100 mV. To reduce it further, your contamination level is to be better than 1 in 10000 and that is a pretty high bar.

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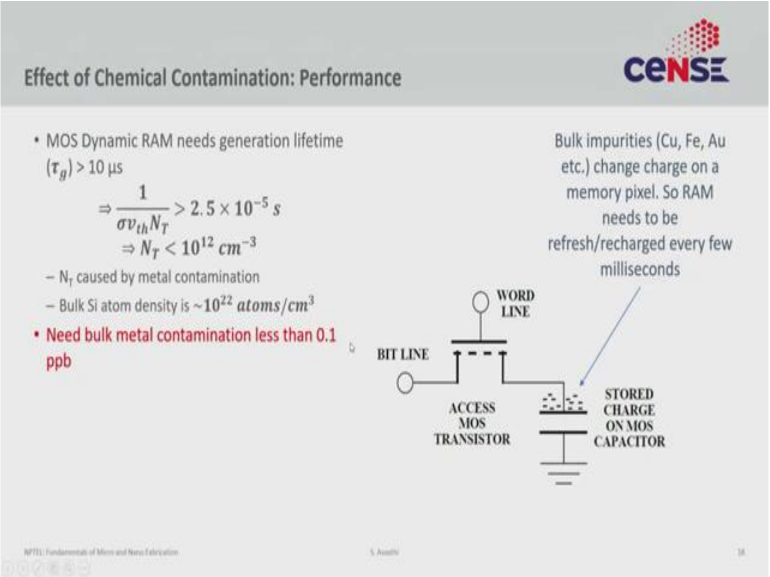

Effect of Chemical Contamination: Performance

- MOS Dynamic RAM needs generation lifetime (τ_g) > 10 µs

$$\Rightarrow \frac{1}{\sigma v_{th} N_T} > 2.5 \times 10^{-5}\, s$$

$$\Rightarrow N_T < 10^{12}\, cm^{-3}$$

  - N_T caused by metal contamination
  - Bulk Si atom density is ~$10^{22}\ atoms/cm^3$
- Need bulk metal contamination less than 0.1 ppb

Bulk impurities (Cu, Fe, Au etc.) change charge on a memory pixel. So RAM needs to be refresh/recharged every few milliseconds

Another example of what contamination can do: this is as RAM. In a RAM, you store charges (on a capacitor) and without going to details, typically you need bulk defect density < $10^{12}/cm^3$. This is not surface, but bulk defect density. Once again, if you compare this with the silicon atomic density ($10^{22}/cm^3$), the bulk contamination needs to be < 0.1 ppb, which is a remarkably low number. A very little amount of contamination either on the surface or in the bulk will cause a significant change in the performance of the device and must not be allowed to happen.

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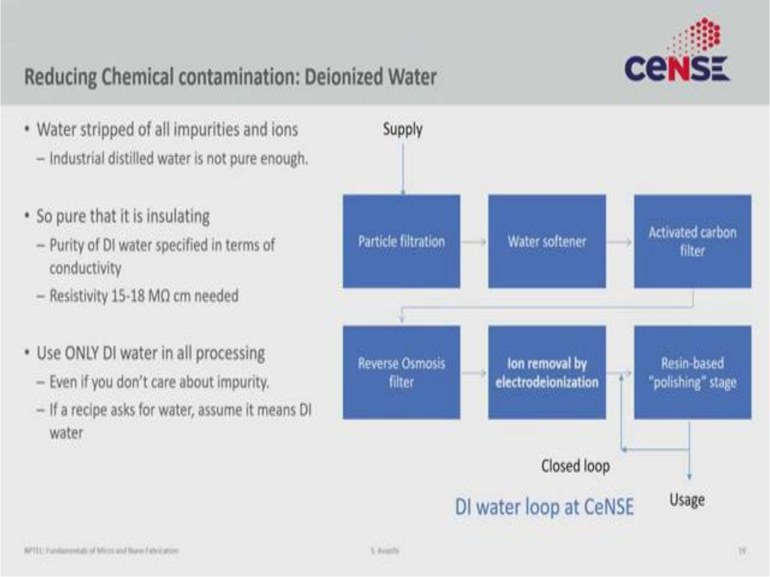

Reducing Chemical contamination: Deionized Water

- Water stripped of all impurities and ions
  - Industrial distilled water is not pure enough.
- So pure that it is insulating
  - Purity of DI water specified in terms of conductivity
  - Resistivity 15-18 MΩ cm needed
- Use ONLY DI water in all processing
  - Even if you don't care about impurity.
  - If a recipe asks for water, assume it means DI water

Supply

Particle filtration

Water softener

Activated carbon filter

Reverse Osmosis filter

Ion removal by electrodeionization

Resin-based "polishing" stage

Closed loop

Usage

DI water loop at CeNSE

For such purity, we need to use the purest form of water we can find. This is called deionized water; purer than distilled water in the sense that it is completely stripped of all the impurities and ions to the point where it becomes insulating. Most people think of water as conducting, which is in most cases, but here we have purified water to a point where it becomes insulating. Making DI water is a very expensive multistage process; start with particle filtration, water softener, activated carbon like a typical kitchen water filter, followed by reverse osmosis, and ion removal by electro-deionization and a resin-based polishing stage.

DI water never remains clean because the air has carbon dioxide that will dissolve and form carbonate ions. Just being exposed to air, deionized water becomes ionized again. In order to keep DI water DI, you have to continuously circulate it in a polishing loop, so, when you are using it, it is of the highest purity. Generally, use only DI water for all the processing even if the paper does not specify it. If it says to use water, it means use DI water. Virtually, under no circumstances inside the cleanroom should you ever use any other form of water.

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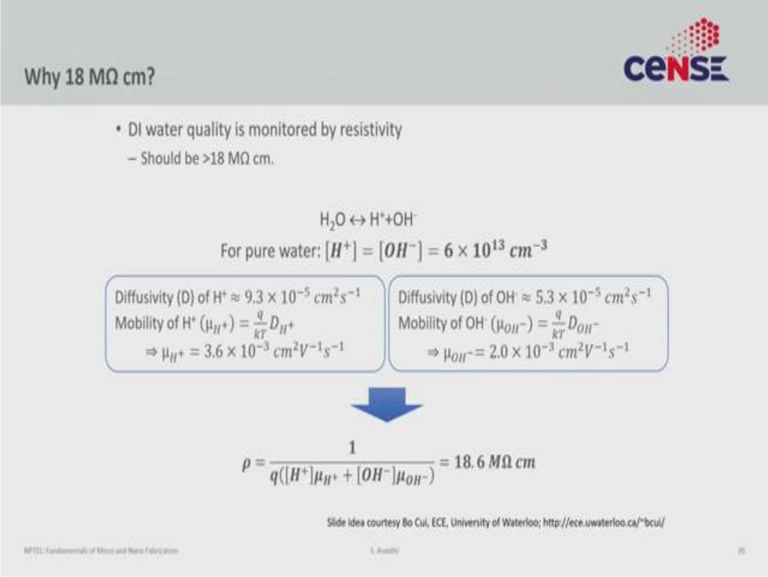

Why 18 MΩ cm?

- DI water quality is monitored by resistivity
  - Should be >18 MΩ cm.

$H_2O \leftrightarrow H^+ + OH^-$

For pure water: $[H^+] = [OH^-] = 6 \times 10^{13}\ cm^{-3}$

Diffusivity (D) of $H^+ \approx 9.3 \times 10^{-5}\ cm^2 s^{-1}$
Mobility of H^+ $(\mu_{H^+}) = \frac{q}{kT} D_{H^+}$
$\Rightarrow \mu_{H^+} = 3.6 \times 10^{-3}\ cm^2 V^{-1} s^{-1}$

Diffusivity (D) of $OH^- \approx 5.3 \times 10^{-5}\ cm^2 s^{-1}$
Mobility of OH^- $(\mu_{OH^-}) = \frac{q}{kT} D_{OH^-}$
$\Rightarrow \mu_{OH^-} = 2.0 \times 10^{-3}\ cm^2 V^{-1} s^{-1}$

$$\rho = \frac{1}{q([H^+]\mu_{H^+} + [OH^-]\mu_{OH^-})} = 18.6\ M\Omega\ cm$$

Slide idea courtesy Bo Cui, ECE, University of Waterloo; http://ece.uwaterloo.ca/~bcui/

DI water becomes insulating in the absence of ionic conduction with a resistivity of about 18.6 MΩ-cm. This number comes from thermodynamics and kinetics. Pure water $[H^+]$ and $[OH^-]$ concentration of around $6 \cdot 10^{13}/cm^3$. For this ion concentration and the ionic mobility in water, the resistivity comes out to be 18.6 MΩ-cm. In our cleanroom for example, we always maintain this number around 18.2.

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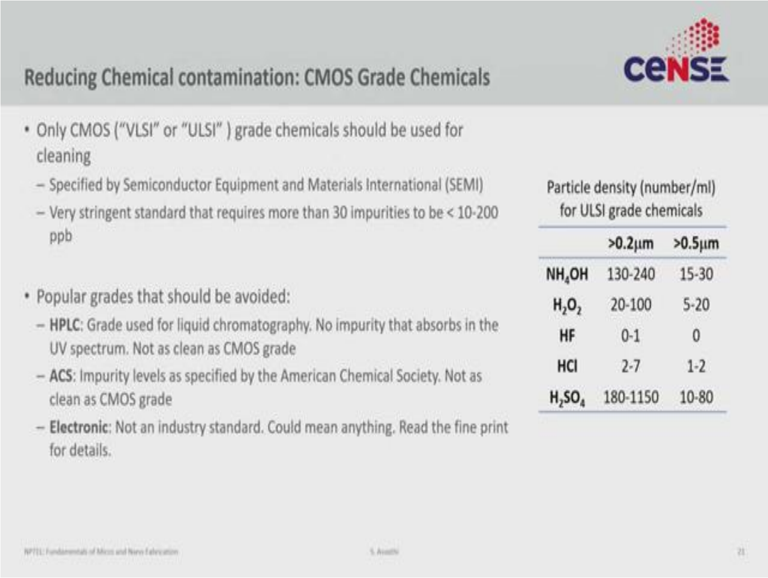

Reducing Chemical contamination: CMOS Grade Chemicals

- Only CMOS ("VLSI" or "ULSI") grade chemicals should be used for cleaning
  - Specified by Semiconductor Equipment and Materials International (SEMI)
  - Very stringent standard that requires more than 30 impurities to be < 10-200 ppb
- Popular grades that should be avoided:
  - **HPLC**: Grade used for liquid chromatography. No impurity that absorbs in the UV spectrum. Not as clean as CMOS grade
  - **ACS**: Impurity levels as specified by the American Chemical Society. Not as clean as CMOS grade
  - **Electronic**: Not an industry standard. Could mean anything. Read the fine print for details.

Particle density (number/ml) for ULSI grade chemicals

	>0.2μm	>0.5μm
NH_4OH	130-240	15-30
H_2O_2	20-100	5-20
HF	0-1	0
HCl	2-7	1-2
H_2SO_4	180-1150	10-80

The second thing we do to reduce chemical contamination is to have ultra-pure chemicals. These are typically called CMOS, VLSI or ULSI grade chemicals. The contamination in these chemicals is extremely low. It is specified by the semi-standard. This is a very stringent standard that actually requires more than 30 types of impurities to be less than 10 to 200 ppb. Along with that, it also has very stringent requirements of what particle density is allowed in these chemicals. By far these are the purest chemicals you can buy on the market. Try to avoid other pure chemical grades that you can get on chemistry websites, for example, HPLC which is actually a liquid chromatography grade or ACS pure grades that are specified by American chemical society. They are not as clean as CMOS grade.

You can also buy electronic grade chemicals. This is not an industry standard and can mean anything. As much as possible, avoid all these weird standards and stick to CMOS chemical if you can find it.

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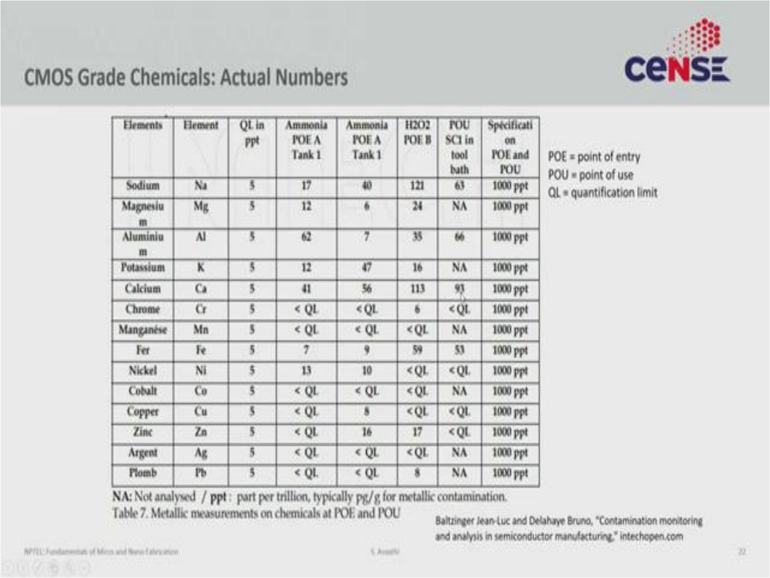

CMOS Grade Chemicals: Actual Numbers

Elements	Element	QL in ppt	Ammonia POE A Tank 1	Ammonia POE A Tank 1	H2O2 POE B	POU SC1 in tool bath	Spécification on POE and POU
Sodium	Na	5	17	40	121	63	1000 ppt
Magnesium	Mg	5	12	6	24	NA	1000 ppt
Aluminium	Al	5	62	7	35	66	1000 ppt
Potassium	K	5	12	47	16	NA	1000 ppt
Calcium	Ca	5	41	56	113	93	1000 ppt
Chrome	Cr	5	< QL	< QL	6	< QL	1000 ppt
Manganèse	Mn	5	< QL	< QL	< QL	NA	1000 ppt
Fer	Fe	5	7	9	59	53	1000 ppt
Nickel	Ni	5	13	10	< QL	< QL	1000 ppt
Cobalt	Co	5	< QL	< QL	< QL	NA	1000 ppt
Copper	Cu	5	< QL	8	< QL	< QL	1000 ppt
Zinc	Zn	5	< QL	16	17	< QL	1000 ppt
Argent	Ag	5	< QL	< QL	< QL	NA	1000 ppt
Plomb	Pb	5	< QL	< QL	8	NA	1000 ppt

NA: Not analysed / **ppt** : part per trillion, typically pg/g for metallic contamination.

Table 7. Metallic measurements on chemicals at POE and POU

POE = point of entry
POU = point of use
QL = quantification limit

Baltzinger Jean-Luc and Delahaye Bruno, "Contamination monitoring and analysis in semiconductor manufacturing," intechopen.com

Here are some examples of contamination inside a CMOS grade chemical. QL is the resolution of the measurement. On the right is the specification from the semi-standard and in the middle are the numbers that they actually found. In most cases, you would see the practically measured numbers are significantly lower than the specifications. Even though the specifications are very stringent, the industry actually manages to get even better numbers.

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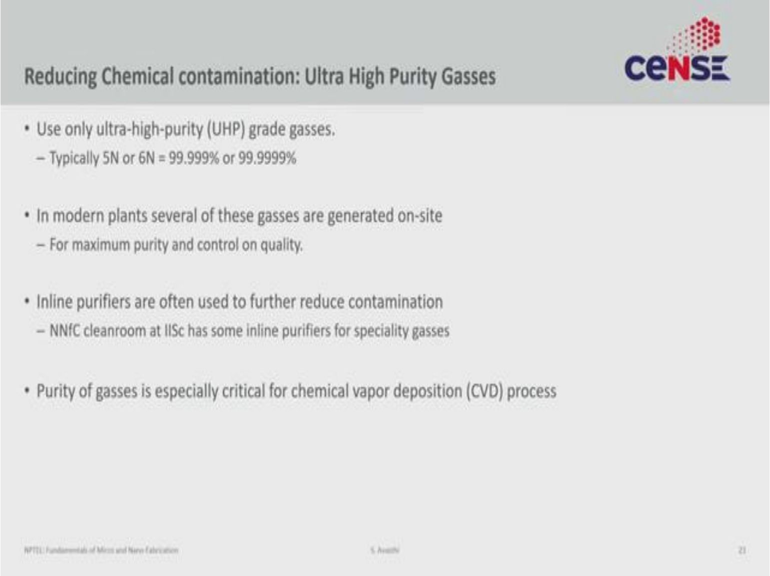

Reducing Chemical contamination: Ultra High Purity Gasses

- Use only ultra-high-purity (UHP) grade gasses.
  - Typically 5N or 6N = 99.999% or 99.9999%
- In modern plants several of these gasses are generated on-site
  - For maximum purity and control on quality.
- Inline purifiers are often used to further reduce contamination
  - NNfC cleanroom at IISc has some inline purifiers for speciality gasses
- Purity of gasses is especially critical for chemical vapor deposition (CVD) process

We also use extremely high purity gasses; typically, 5N or 6N which is 99.999 or 99.9999 %. In a modern plant, several of these gasses are generated on-site for maximum purity and control. In very specialized cases we also have inline purifiers to further purify the gas at the point of use. This purity is extremely critical for a process like CVD. We will discuss CVD a couple of lectures later.

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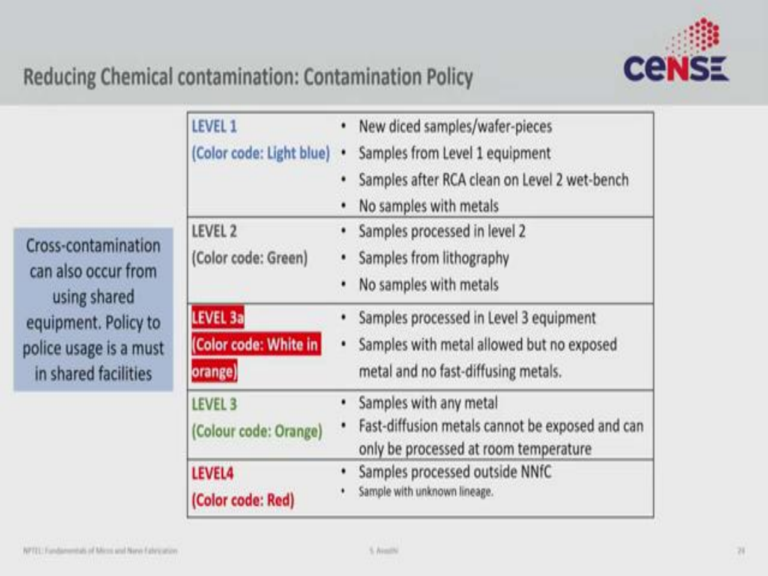

Reducing Chemical contamination: Contamination Policy

CeNSE

Cross-contamination can also occur from using shared equipment. Policy to police usage is a must in shared facilities

LEVEL 1 (Color code: Light blue)	• New diced samples/wafer-pieces • Samples from Level 1 equipment • Samples after RCA clean on Level 2 wet-bench • No samples with metals
LEVEL 2 (Color code: Green)	• Samples processed in level 2 • Samples from lithography • No samples with metals
LEVEL 3a (Color code: White in orange)	• Samples processed in Level 3 equipment • Samples with metal allowed but no exposed metal and no fast-diffusing metals.
LEVEL 3 (Colour code: Orange)	• Samples with any metal • Fast-diffusion metals cannot be exposed and can only be processed at room temperature
LEVEL4 (Color code: Red)	• Samples processed outside NNfC • Sample with unknown lineage.

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Finally, there is also some sort of contamination policy. It is especially important in common facilities which are used by several groups or several people. Equipment that is used for one purpose can accumulate a certain type of contamination that is bad for another. To keep the output consistent, the purity of the tool has to be maintained. You do that by restricting the substrates and the material that actually go inside. This is an example of something that we do at IISc, some version of this exists in virtually every common-use facility, where we give levels to each equipment and you are only allowed to put a certain type of substrate with a certain type of contamination profile into that tool.

Level 1 tools tend to be the cleanest, level 4 tools tend to be the dirtiest and you are not allowed (unless in special circumstances) to go from level 4 to level 3 or from level 3 to level 2. You can only go from top to bottom, so, you have to map your process in a manner that is consistent with the contamination policy of the cleanroom.

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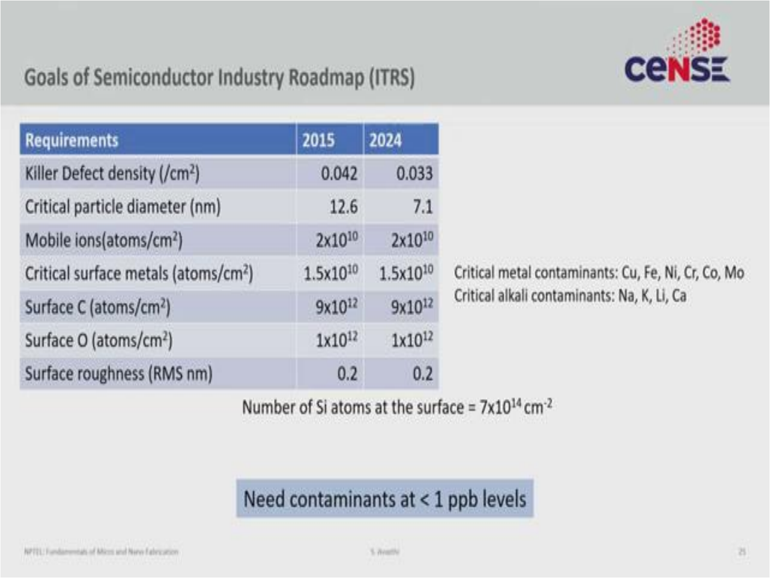

Goals of Semiconductor Industry Roadmap (ITRS)

Requirements	2015	2024
Killer Defect density (/cm^2)	0.042	0.033
Critical particle diameter (nm)	12.6	7.1
Mobile ions(atoms/cm^2)	2×10^{10}	2×10^{10}
Critical surface metals (atoms/cm^2)	1.5×10^{10}	1.5×10^{10}
Surface C (atoms/cm^2)	9×10^{12}	9×10^{12}
Surface O (atoms/cm^2)	1×10^{12}	1×10^{12}
Surface roughness (RMS nm)	0.2	0.2

Critical metal contaminants: Cu, Fe, Ni, Cr, Co, Mo
Critical alkali contaminants: Na, K, Li, Ca

Number of Si atoms at the surface = 7×10^{14} cm^{-2}

Need contaminants at < 1 ppb levels

ITRS is an industry body that lays down the roadmap of where the industry needs to be several years from today. For example, this is where we are in 2015 and ITRS reads out the numbers that they would like to achieve in 2024. They move towards most stringent requirements for the amount of surface contamination, critical metal contamination etcetera, in most cases, < ppb. If you want to understand or get an intuition about how small this number is, compare it with the surface ($7\cdot10^{14}$/cm^2) or bulk (10^{22}/cm^3) atomic density to get a sense of what % purity we are talking about.

So, with that introduction to fab, let us now get into how we keep our wafers clean.

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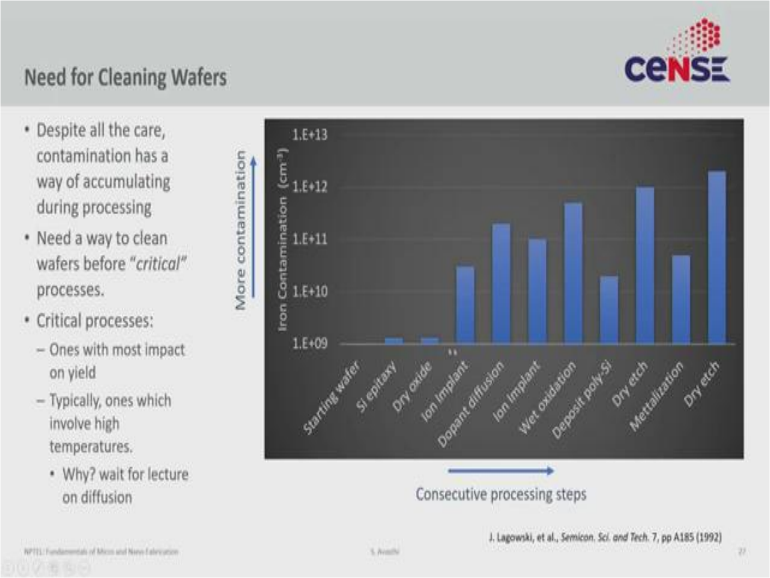

Need for Cleaning Wafers

- Despite all the care, contamination has a way of accumulating during processing
- Need a way to clean wafers before "*critical*" processes.
- Critical processes:
  - Ones with most impact on yield
  - Typically, ones which involve high temperatures.
    - Why? wait for lecture on diffusion

J. Lagowski, et al., *Semicon. Sci. and Tech.* 7, pp A185 (1992)

You start with the wafer that is very clean and process it in an ultra-clean room. As you do multiple processes, just the fact that you are interacting with this wafer, you start accumulating contamination on the wafer. This is a log scale, so, towards the end of your processing step, the contamination might be 1000 times more then what you started on a virgin wafer. The only way we are able to manage this is before critical steps (defined as critical by the user), we clean trying to reduce this contamination back to lower level so that it does not propagate in the whole wafer.

Typically, critical processes are the ones that create the most impact on yield. These typically are high-temperature steps. So, before every high-temperature step, you want a cleaning step. Why high temperature is something you will appreciate more when we discuss diffusion. With that introduction of what is a fab, why do we need a clean room, what are the standards when we talk about a clean room we will end this lecture.

In the next lecture, we will go into more detail on how we actually do the cleaning. Even though we have a clean room the wafers will become dirty. So, we must have a way of cleaning that surface. See you next time.