<u>Chip manufacturing for Smart Wearable Healthcare Devices</u>

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Introduction: An integrated circuit or a chip is one of the most significant innovations of the 20th century. In the last five decades, advances in physics, chemistry, and material science have brought us from room-sized transistors to micro-chips containing billions of transistors that can fit on the tip of our fingers. Electronics are at the heart of technological advancements, and processing chips are the most critical players in bringing to life increasingly smarter and compact devices to our lives. In addition to compactness, other goals that are leading the progress are making devices energy-efficient, high performance, ecologically sustainable. With these goals in mind and looking at the needs of the world 'today,' this report talks about the manufacturing processes and materials behind the chips to be used in wearable healthcare devices. We also discuss how the hardware in electronics is evolving to cater to specific needs in the medical and healthcare sectors and the newer goals to incorporate the Internet of Things (IoT) into personal health and fitness monitoring.

Background: A processor or a chip is a micro/nanoelectronic device that can process information via electrical currents (movement of charged particles) along a circuit. Chips harbour complex connected ensemble of transistors and gates which facilitate information processing. Transistors can be thought of as switches which either allow or prevent a signal to pass and amplify or modulate the passing signal, gates produce the electronic signal output (0 or 1) and together, gates and transistors form a circuit which can 'process' data.

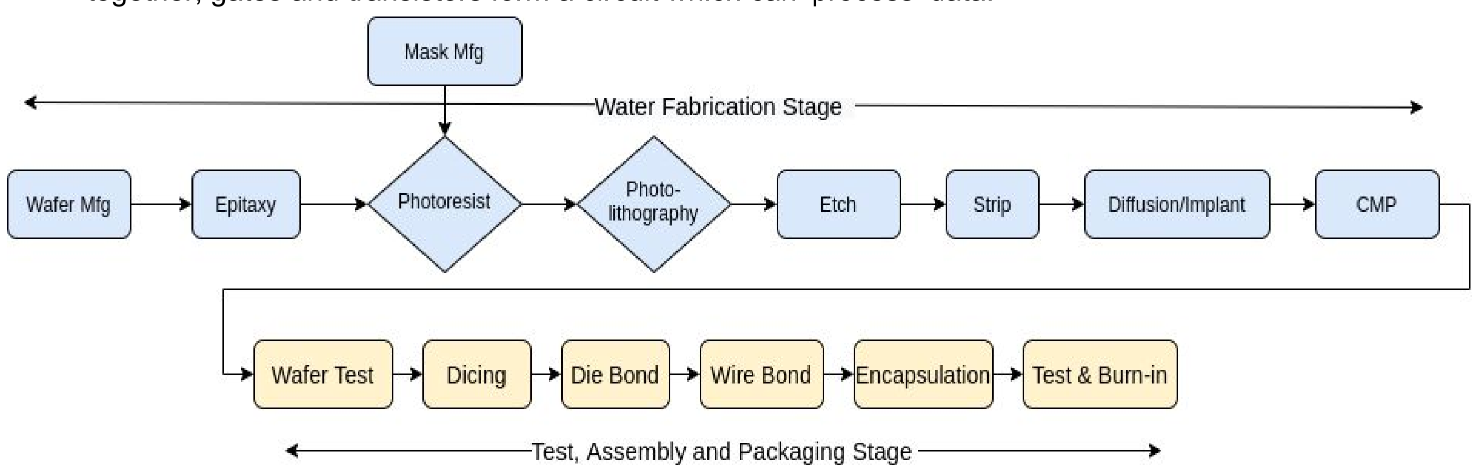

Figure 1. Semiconductor Manufacturing Process

Wafer Manufacturing

- <u>Czochralski Process</u>: Czochralski process is the most commonly used process for creating single-crystal silicon. A small piece of single crystal (known as seed crystal) silicon is dipped into high purity molten silicon. At first, the seed crystal is pulled out of the crucible rapidly (*Dash Process*)[1]. This reduces the initial diameter of the cylinder to a few millimetres and ensures a dislocation free crystal. The diameter is later adjusted by slow draw, which increases the diameter. The seed crystal is then slowly pulled out of the molten silicon while being rotated simultaneously. The crucible is also rotated in the opposite direction while the seed is being pulled out; this helps in minimizing the effects of convection in the melt. Pulling speed, rotation speed, and the temperature gradient all affect the size of the single crystal. The cylinder of silicon pulled from the crucible is called an ingot.[2]

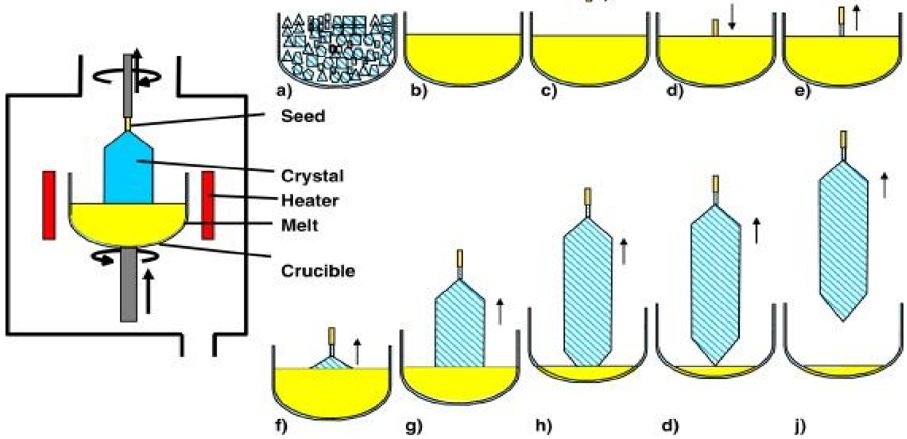

Figure 2. Czochralski Process

- Wafer Slicing: The ingot created in the czochralski process is generally one to two meters long, and needs to be cut into thin wafers or slices. The ingot is ground to achieve a desirable diameter, then cut into thin wafers using diamond-tipped saws. The wafers are evened down to a uniform, predefined thickness by removing the surface layers damaged during the cutting process. The damaged surfaces are further cleaned and polished first using an etching solution and then using ultrapure deionized water.

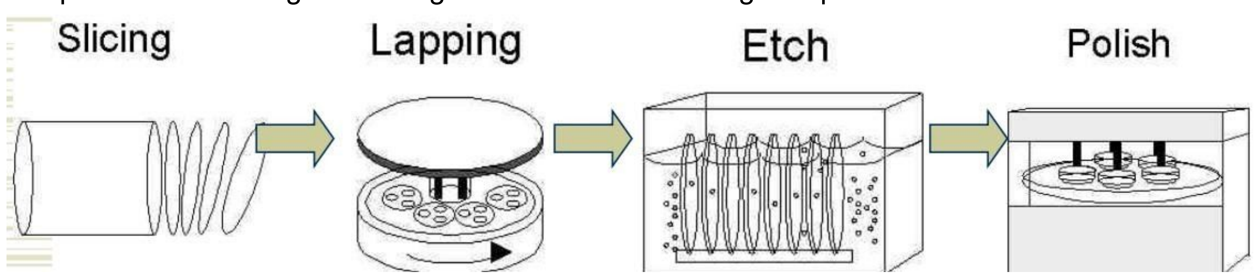

Figure 3. Wafer Slicing [3]

Photolithography

The Si-wafers obtained after slicing, and further processing is about 500 microns thick and 50-300 micron in diameter. Before further processing, the wafer is covered in a layer of SiO_2 using thermal oxidation or chemical vapour deposition (CVD). The wafer is covered in SiO_2 since SiO_2 can be etched away with hydrogen fluoride-based etchants, whereas pure silicon can't. The HF etchant is used to create windows in the SiO_2 layer during photolithography, as shown in Fig. 4 below.

First, we coat the wafer (substrate) with a photosensitive polymer (called the photoresist) using a device called the spin coater. The substrate is then baked in an oven. The next step involves exposing limited regions of the photoresist covered substrate to UV-light through a patterned mask. The part of the photoresist exposed to the UV-light is removed, leaving windows to access the SiO_2 layer. The part covered with the mask during UV-light exposure remains intact and covered in the photoresist. The SiO_2 windows are then removed using an HF-based etchant, leaving windows to pure silicon layer of the wafer. The photoresist is then removed. The window in the SiO_2 layer can now be used for dopant incorporation into the Si-wafer. As shown in part A of the figure below, we can introduce a p-type dopant into the wafer through the window.

Using the photolithography steps described above, we create another window into the SiO_2 layer and incorporate the n-type dopant into the wafer. Now that the wafer has both n and p-type parts, it can be used as a PN-junction by depositing a thin metal film to make contact with both n and p-type parts of the substrate. In practice, another patterned layer of protective covering is used to cover the whole PN-junction.

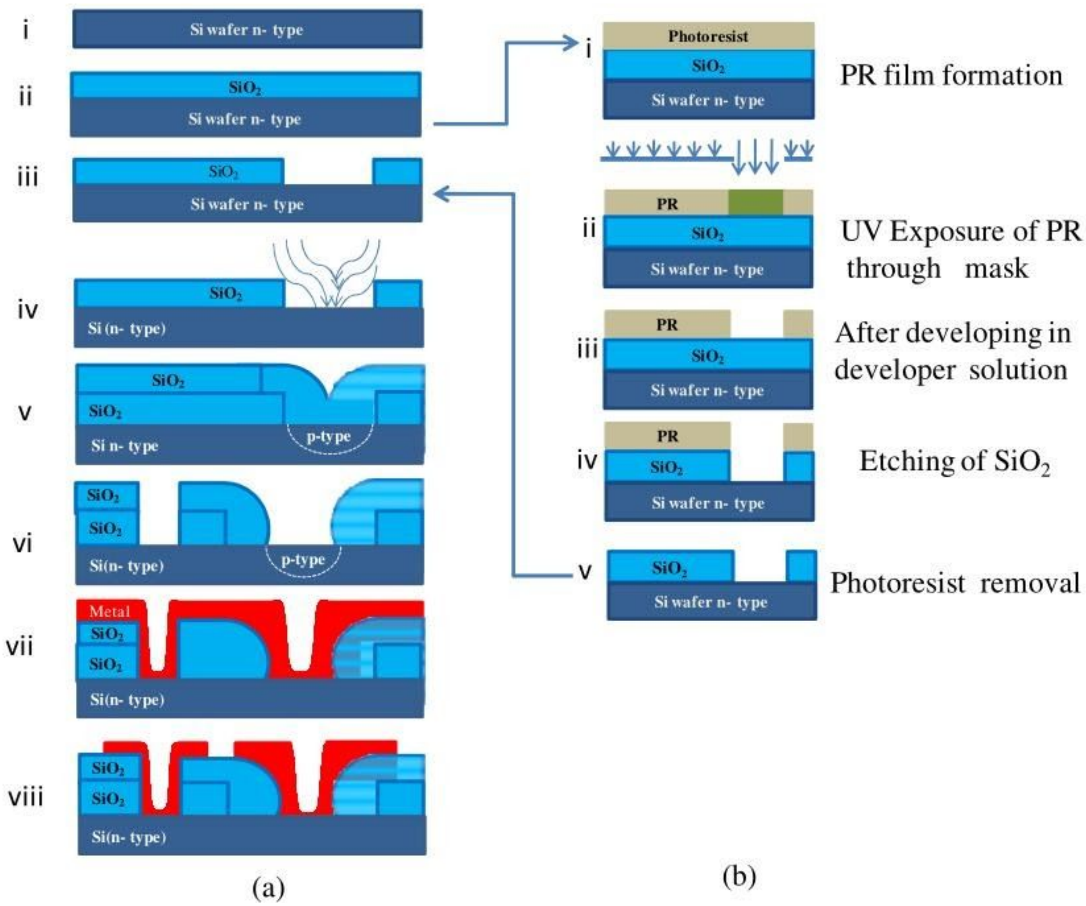

Figure 4. a) Processing steps in developing a PN-junction b) Steps involved in photolithography

Dopant incorporation

Silicon, in itself, has a minimal utility as a semiconductor. Therefore, it is generally doped with other elements to change the local conductivity and make p-type or n-type semiconductors. Group 15 elements such as Phosphorus and Arsenic are used as n-type dopants, whereas 13th group elements like boron are used as p-type dopants. Doping in microelectronic devices is generally carried out by the following two processes.

- Diffusion: In diffusion, the Si surface is exposed to the dopant source (generally a gas). The dopant is incorporated in a thin surface layer in a short duration under low temperature. The gas is then removed, and the diffused dopant is redistributed under higher temperature and pressure conditions.
- Ion Implantation: In ion implantation, the Si wafer is exposed to a flux of ions. The ion beam is created from an appropriate gas source of dopant (e.g., boron fluoride for boron). The gas source is first ionized, and the ions are accelerated to high energies up to a few hundred keV. Ions thus created are a mixture of several different elements and are passed through analyzing magnets that select ion beams of specific elements, like B+(for p-type) and As+(for n-type). The energetic ions that hit the Si wafer penetrate into the surface up to a depth of 10-100 nm. The depth of penetration depends on the energy of the ions, which can be controlled very minutely, unlike diffusion. The concentration of dopant in the wafer can also be controlled by controlling the ion-flux, which results in more precise concentrations compared to diffusion.

Cleaning

The cleaning process is repeated after every step discussed above. Cleaning after a step is important as microchip manufacturing requires ultra-pure wafers at every stage to produce contamination-free chips, and the contamination can even come from residues from various steps. The cleaning process to be used largely depends on the material of the wafer. RCA (named after the Radio Corporation of America) is a typical cleaning process.

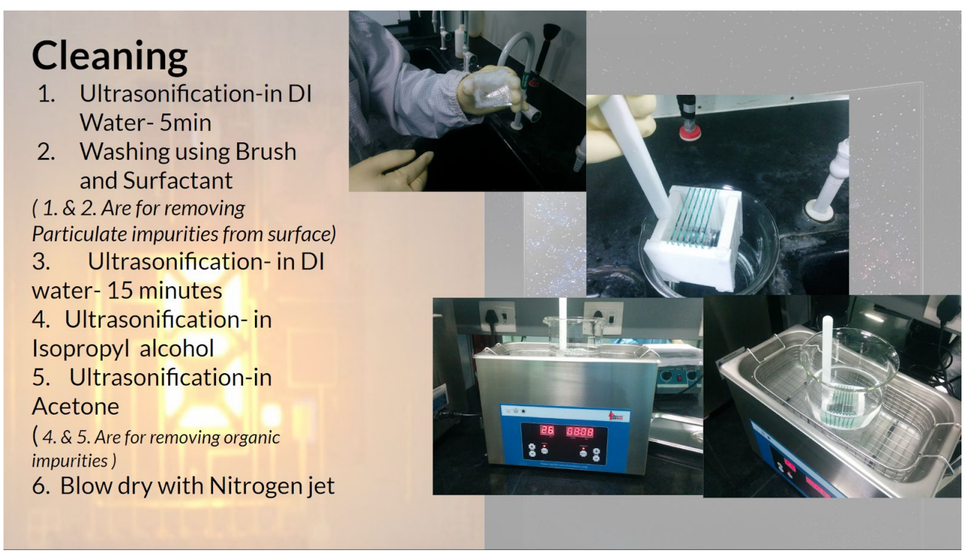

Figure 5. Images taken at FlexE IIT Kanpur of Cleaning Process

After wafer processing is done, each chip is tested for its functionality in the sort-testing process.

Wearable devices

Wearable devices are worn on the skin and come in various forms like wristbands, eyeglasses, watches, shirts, headbands, etc. They have revolutionized healthcare and fitness monitoring, and are non-invasive and convenient. The devices contain sensors that gather the data, and it is fed into the processor as well as the database of any linked applications, the analysis can be very informative to the wearer about how they are doing, analysis can help predict patterns and abnormalities in heath. Various kinds of parameters are sensed like the body vitals, including temperature, heart rate, rate of respiration, blood pressure, and other biomarkers taken from body fluids (saliva, sweat, tears) as well as breath.

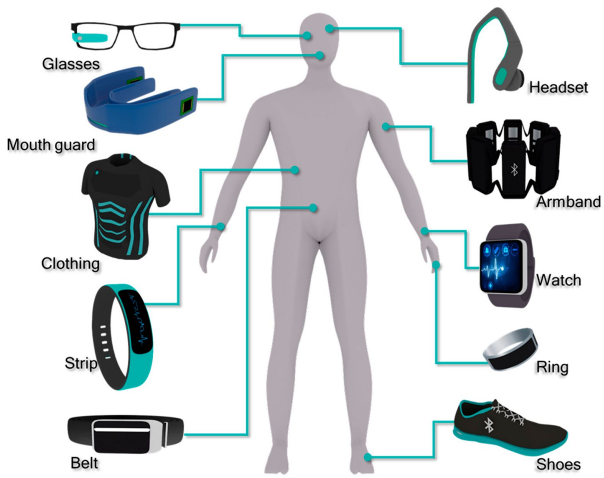

Figure 6. Portable medical and healthcare devices worn on body parts [6]

Source	**Physiological parameter**	**Sensing devices**
Skin	Temperature	Ressistometric sensor Field Effect Transistor Infrared detector (non-contact)
Odour	Volatile Organic Compounds	Resistometric Sensor Colorimetric Sensor
Pressure	Heart/respiration pulse Motion posture	Piezoelectric sensor Capacitive sensor
Sweat	Metal ions Lactate Uric acid pH Ammonia Skin humidity	Potentiometric sensor Amperometric sensor Voltammetric Sensor Colorimetric sensor
Physical activity	Foot Motion/ step Count Sitting Time Sleep Schedule	Motion Sensor Gyroscope Accelerometer Pedometers

Table 1. Various sensors that are used in health monitoring devices

The devices should comply with the following criteria:

1. High **sensitivity** to changes in the physiological index: The changes in the body, even the very subtle ones, can indicate early symptoms of infection and more. For recording very slight changes in the human body, the materials used should have high sensitivity.
2. Adequate **Limits** for detection/ high Response: Signals and data from the human body are generally low signal regime, and an adequate detection limit is needed in the response materials.
3. **Compatibility** with Human Skin and Body: The design has to be flexible, stretchable, and should not cause skin irritation, so biocompatibility is needed on moist skin.
4. **Low Power** Consumption: these devices target low power consumption standards that enable a prolonged “always-on” functionality, preferably utilizing energy generated by body movements.
5. **Design** Challenges: weight, the shape should not affect natural body movements and should be shock, vibrations resistant; should not heat up or trap heat on prolonged usage;

PULP microprocessors: The new processor is called PULPino, and it is designed and heavily researched by Swiss and European research institutions, it is extremely low energy consumption (PULP stands for ‘parallel ultra-low power’).

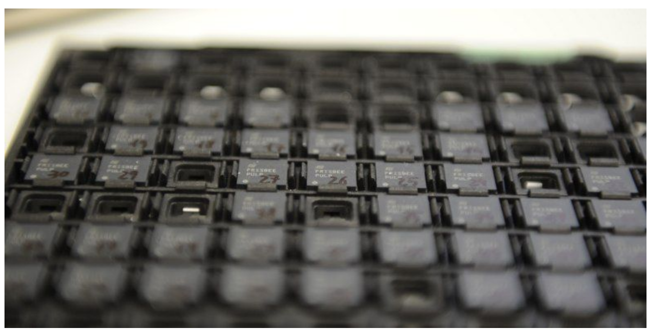

Figure 7. Network of PULP microprocessor chips on a tray. PULPino chips are smaller, depending on technology and memory size as small as 1 x 1 millimeter. Credit: ETH Zurich [5]

Hardware designs and software source codes for smart devices are generally very guarded trade secrets by companies, but these days many many open-source products exist. Open microcontroller boards like Arduino and Raspberry Pi based on commercial chips are open-source. PULPino similarly is open-source and maximizes the freedom to developers and researchers to use and modify the systems. This is especially important in modern-day times to promote innovation. These chips are ideal for small devices, such as smartwatches, sensors for healthcare monitoring physiological functions (which can communicate with a heart rate monitor, for instance) or sensors for the Internet of Things.
For example, a smartwatch powered by the PULP processor comes with a micro-camera that analyzes visual information and wearer's location and whereabouts . The challenges in this have been to accommodate the circuits in a small area as well as provide efficient computing capacity. It is said that the production of microchips with prototypical designs has become

relatively cheap in recent years because semiconductor manufacturers have production capacities that are large. The key process, which is expensive both in time and effort, is designing. It would be taxing in terms of engineering efforts to design a complex microprocessor from scratch, so these days most companies buy pre-designed functional components, and they integrate and assemble them according to their needs. New research and progress in development are aimed at, by open-sourcing the designs.

Healthcare device prototype:

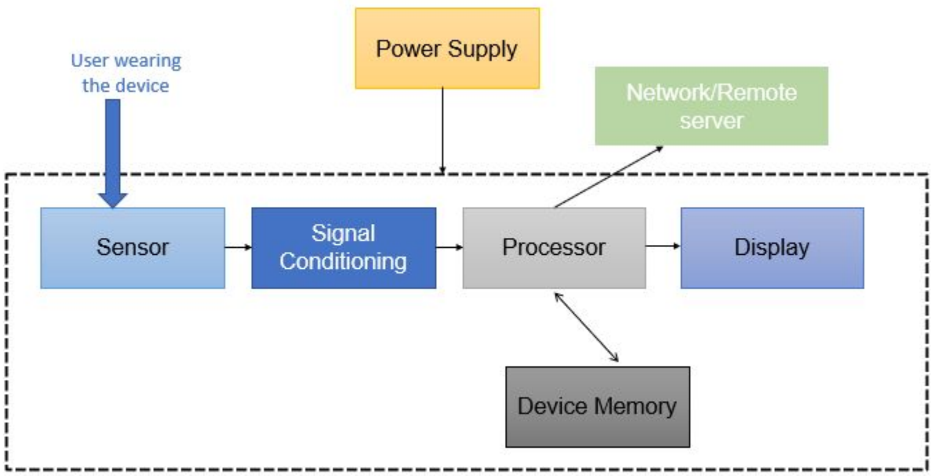

Figure 8. Components of a standard smart healthcare device

- Sensor: To gather the signal of interest from the body or environment, various sensors are mentioned in Table 1.
- Signal Conditioning: amplifier filters to enhance the signal and reduce noise
- Processor: Includes an A/D (analog to digital) board and circuitry for computations (interpretation and execution of encoded instructions on the data, also includes a module for wireless communication
- Memory: To save obtained data for future reference and analysis
- Display: On-screen user interface to output data

Wearable devices should be complementary to the hospital medical aid. They should provide reliable health monitoring, aim at improving the living of chronic-illness patients as well as help in forming a network to quickly identify who needs help and where.

Printing Technology and Roll-to-Roll Production: Printing sensors and electronics on flexible substrates is a key to make wearable devices fabrication and manufacturing low cost and large scale. A large number of printing techniques have evolved in the past few years.

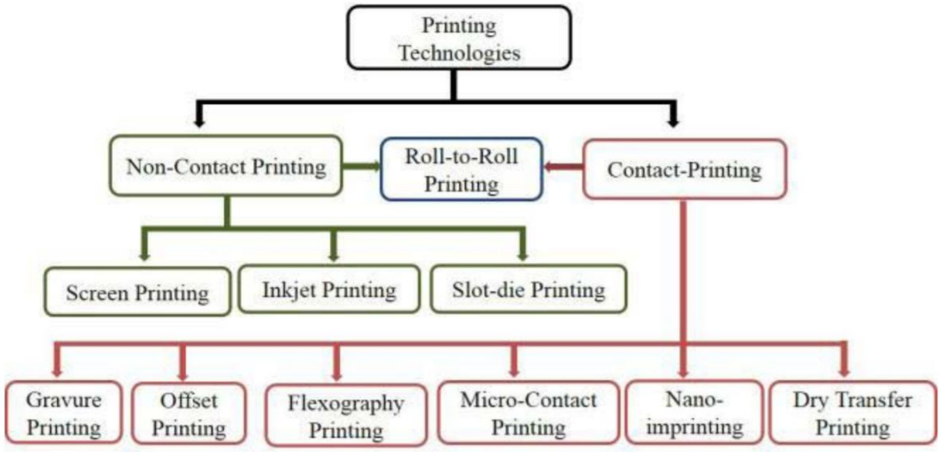

Figure 9. Various Printing Technologies for electronics [12]

We have developed a lot of solution-processable materials as well as dry transferable monocrystalline materials with characteristic electronic properties: conductors, semiconductors, and dielectrics. We also have composite materials that are functionally insulators, piezoelectric, piezoresistive, ferroelectric, and photosensitive.

Among the metals which are commonly used in printing the electrodes, Ag (silver) based pastes are most common. They have good electrical properties on flexible plastic surfaces. Organic Conducting organic materials can be fine-tuned to get the desired properties. Most common PEDOT:PSS as it is transparent and highly conducting (300 S/cm). In semiconductors, Silicon either by solution processing or nanoparticles can be used with annealing temperatures (550°C to 750 °C), in organics P3HT, PQT, fullerenes have tunable charge transport and mobility. Flexible substrate materials majorly used is PET (polyethylene terephthalate), it is a semi-crystalline polymer and has good bendability, transparency, etc.

A. **Screen Printing**: It is the most conventional of all printing techniques. The deposition is controlled, speed is fast and it is versatile. The desired pattern is defined by open areas on the mesh. The ink is mostly in the form of pastes.

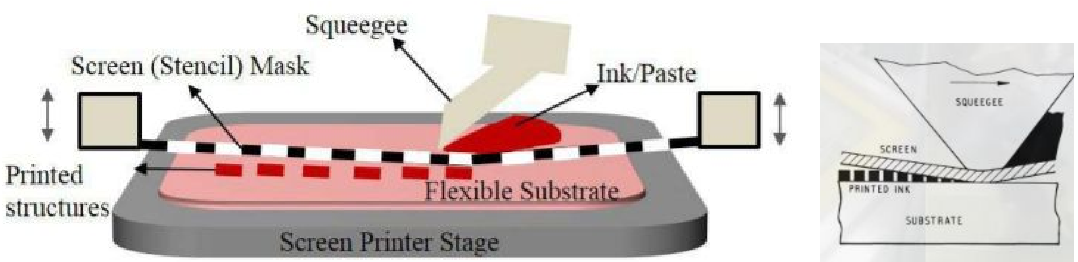

Figure 10. Mechanism of screen printing [12]

Parameters for screen printing squeegee pressure, squeegee speed, squeegee angle, squeegee hardness, gap between screen and substrate, mesh size of screen, emulsion thickness, tension in the screen, viscosity of paste, wear and tear of squeegee on reuse as well as room temperature. These parameters are adjusted to achieve the required thickness and connectivity of the layer printed.

Challenges in screen printing are that very high resolution uniform line patterns are not possible of size less than 30 microns. High viscosity of ink is required, drying out of ink on the screen is an issue and also ink wastage and the roughness of the printed layer is generally very high.

B. **Inkjet Printing:** Viscosity of the ink is low, the droplets of ink are ejected, controlled by various actuation phenomena like thermal, piezoelectric, electrostatic driven printers.The deposition of droplets is very position specific and hence high resolution can be achieved. Material wastage is low. The key challenges are controlling the ink-substrate interaction to ensure proper wetting and functionality and avoiding the breaking of the film or formation of pinholes, splashes while drying of ink or sintering, the printing speed is relatively lower although multi nozzle parallel set-upas are being made

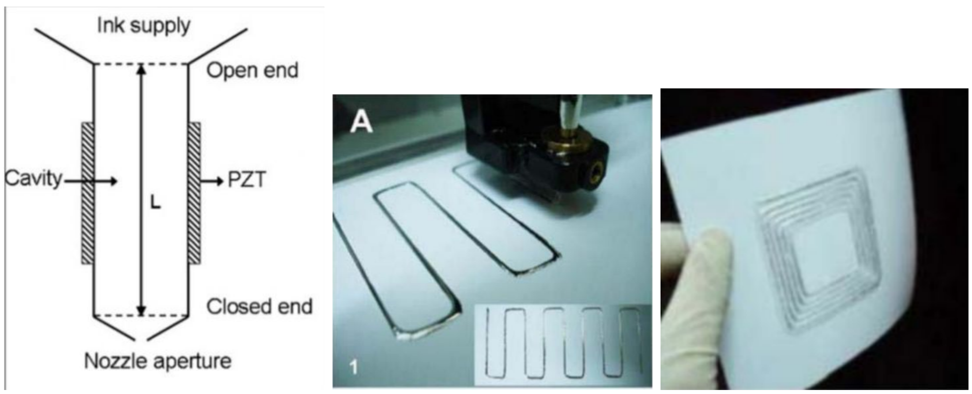

Figure 11. Nozzle of inkjet printer, Metal conductor lines for printed as an inductance coil [10]

R2R: The final goal of all these newer technologies is to ensure a fast and industrial scale, efficient production of electronics. Various laboratories and industry-research units have been trying to develop highly optimized processes, understanding the relationships between various fabrication processes, functional materials, substrates, solvents, drying and annealing techniques etc. To merge various printing techniques and fine-tune the exact process parameters with the aim of moving the substrates at high speeds of 5-50m/minute. Roll-to-Roll manufacturing is aimed at high, continuous throughput. Apart from integrating various printing instrumentations, R2R setup includes many rollers over which the flexible substrates pass. The printing technology is low cost on large scales, and the temperature of processing is low. Very significant progress is made in the design aspects, technical advancements and process capabilities of printing technologies.
Printed technologies are also incorporating various 2D materials like graphene for building smart devices in healthcare and fitness monitoring.
Some prototypical ideas are, for example, a patient can wear a printed graphene-based RFID (Radio Frequency Identification) on the arm which senses and records body temperature, heartbeat and sends it back to the database. The medical monitoring is highly simplified and organized. Dr Zhirun Hu from the University of Manchester and his group has been developing printed graphene devices with antennas and tested their communication with mobile devices through wifi and other transmission technologies, to develop skin attachable mobile communication healthcare devices. Various companies are working on achieving and implementing these technologies and reducing manufacturing costs.

Figure 12. Image of a Roll-to-Roll (R2R) setup in a clean room environment with different printing process units installed in the production line [11]

Conclusion: Wearable healthcare monitoring devices which connect to the network are more important today than ever. Having a complete data analysis of the body's physiological conditions, also mental health markers etc. can lower the burden on the country's healthcare system and help establish a web where it is easy to pin-point 'where,what and who' needs assistance. At the heart of sensors and smart devices lie electronic circuits and this report has covered various steps in the fabrication of chips from traditional to newest, we have also discussed challenges and requirements of this field and how the research and industry are progressing to achieve newest designs. Also, with the increase in the amount of healthcare data from around the world, the medical industry can benefit a lot standing at the edge of machine learning and AI technologies. The systems and processors should have analysis power to notice abnormalities, auto-first aid and medical advice administration, altering the nearest hospitals and maintaining an electronic record of each person within the web.

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