

## **PHYSICAL BACKGROUND OF MEASUREMENT TECHNIQUES IN ADVANCED TECHNOLOGIES**

**Rajfa Musemić**

**University of Sarajevo, Faculty of Mechanical Engineering,  
Vilsonovo šetalište 9, 71000 Sarajevo, Bosnia and Herzegovina**

### **ABSTRACT**

*In this lecture the basic and acceptable to a certain level explanation of the physical processes that underlie the fundamental working process /mode/ many measurement techniques is provided. These are actually the physical processes that enable the functioning of many modern measuring/technical instruments, which are widely used in scientific laboratories and today's technologies. Examples of those are electrical sensors found in circuits, magnetic field sensors, specific mechanical sensors, mass flow and stress/strain sensors, various interferometers and spectrometers, atomic probe microscope (AFM) and scanning tunneling microscope (STM) used for exploring properties of materials etc. Special attention is paid to the instruments used in crystallography, to commemorate the centennial of Nobel Prize in Physics “for the discovery of the diffraction of X-rays by crystals”, given to Max von Laue, as well as to the measurement techniques for environmental issues research. In the end we focus on potential applications of physical principles in measuring instruments, which rely on development of novel materials, like graphene's sensors and superconducting SQUID magnetic field sensors.*

**Keywords:** advanced measurement techniques, sensors, optical instruments, AFM, STM, SQUID

### **1. INTRODUCTION. THE NATURE SCIENCES AND TECHNOLOGY**

Since physics is a fundamental natural science, experimental examination constitutes its backbone. As a confirmation of this statement famous physicist Lord Kelvin (William Thomson 1824-1907, widely known for determining the correct absolute zero value as  $-273.15$  Celsius): “*When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts advanced to the stage of science.*”

Physics is most responsible for the development of technology and closely linked to the development of measuring device in technique. Without physics we could not understand the world in which we live. Physics makes the fundament for many things, starting from the transistors, computers til the lasers. All this is based on quantum physics, actually on modern physics today. Practically, everything that we have in the modern world has been developed thanks to the discoveries in physics.

If someone wants to explain the role of physics in the measurement's techniques, it is necessary to connect the science and technology, to explain the principles of technology itself, especially in terms of physics. Close to the physics is technology and the overall development of society. As long as there have been people, there has been technology. Indeed technology is a powerful force in the development of civilization, all the more so as its link with science has been forged [1]. In the broadest sense, technology extends our abilities to change the world: to cut, shape, or put together materials; to move things from one place to another; to reach farther with our hands, voices, and senses. Technology draws on science and contributes to it's development.

Engineering, the systematic application of scientific knowledge in developing and applying technology, has grown from a craft to become a science in itself. Scientific knowledge provides a means of estimating what the behavior of things will be even before we make them or observe them. Moreover, science often suggests new kinds of behavior that had not even been imagined before, and

so leads to new technologies. Engineers use technology, actually knowledge of science, especially of physics, together with strategies of design, in order to solve practical problems. In return, technology serves as eyes and ears of science [1] .

As technologies become more sophisticated, their links to science become stronger. In some fields, such as solid-state physics (which involves transistors and superconductors), the ability to make something and the ability to study it are so interdependent that science and engineering can scarcely be separated. New technology often requires new understanding of physical phenomena; new investigations often require new technology. It is known that engineering combines scientific research, mathematical modelling and practical values. Scientists seek to show that theories fit the data; mathematicians seek to show logical proof of abstract relations; physicists seek for phenomena in nature that may serve as bases for a certain scale technology measurements; engineers seek to demonstrate that designs work. Scientists cannot provide answers to all questions; mathematicians cannot prove all possible relations; engineers cannot design solutions for all problems [2] .

Knowledge and understanding of physical processes that enable the functioning of many modern measuring/technical instruments, which have widespread use in modern technology and scientific laboratories has significance in terms of the use and development of new devices. The basic physical phenomena and principles of how the processes are flowing in the nature are the fundamental for making and designing measurement's instruments.

In the physics, quality assurance and engineering, measurement is the activity of obtaining and comparing physical quantities of real-world objects and events. Established standard objects and events are used as units, while the process of measurement gives a number relating the item under study and the referenced unit of measurement. Measuring instruments, and formal test methods which define the instrument's use, are the means by which these relations of numbers are obtained. Scientist engineers and other humans use a vast range of instruments to perform their measurements. These instruments may range from simple objects such as rulers and stopwatches to electron microscopes and particle accelerators.

Physics is based on a relatively small number of fundamental laws, but from such a small number of laws results enormous number of experimental facts. To this aim, special attention is given to conservation laws in modern physics, from the classic laws of conservation of energy, momentum, charge and to the special conservation laws in microworld. Conservation laws in physics are usually the result of some underlying symmetry in the universe (Noether's theorem: one of the most important conclusion of theoretical physics which all conservation laws in the nature explains as the consequence of symmetries, i.e. as result of invariance of physical system with respect to some transformation, as well as energy transformation). The law of conservation of energy is the consequence of invariance to the time shift, law of momentum conservation is the consequence of invariance to the spatial displacement, but law of angular momentum conservation is the consequence of invariance to the number of rotation. An interesting fact is that the requirements for greater accuracy of measurements have led to new discoveries in physics, especially in the application of physical principles in measurement's techniques.

## **2. MAIN PHYSICAL PHENOMENA IN MEASUREMENT TECHNIQUES - OVERVIEW**

Now we will make an overview of the most important processes and phenomena passing through some areas of physics. The main phenomena that have left a significant impact on the development of instruments and measurements will be selected and briefly discussed. At the end we will show the basic physical concepts used in nanotechnology with structures at the atomic and molecular level.

For the explanation of any physical process it is necessary to know the physical quantities. The physical quantity qualitatively and quantitatively describes a measurable property of some physical process or state. It enables defining the physical phenomena and its mathematical formulation.

### **2.1 Mechanics**

Mechanics is the branch of physics that deals with the action of forces on bodies and with motion, comprised of statics, kinematics and general dynamics. No matter what is someone's interest in science or engineering, mechanics is important - motion is a fundamental idea in all of science. The principles of mechanics have been applied to three general realms of phenomena. The motions of such celestial bodies as stars, planets, and satellites can be predicted with great accuracy thousands of years before they occur. As the second realm, ordinary objects on Earth down to microscopic size (moving

at speeds much lower than that of light) are properly described by classical mechanics without significant corrections. The engineer who designs bridges or aircraft may use the Newtonian laws of classical mechanics with confidence, even though the forces may be very complicated, and the calculations lack the beautiful simplicity of celestial mechanics. The third realm of phenomena comprises the behavior of matter and electromagnetic radiation on the atomic and subatomic scale. Classical, continuum and relativistic mechanics are built on the fundamental laws like Newton's, Hook's, tension, deformations, relativity, oscillations and waves and laws of conservation (mass, linear momentum, energy and angular momentum).

The installation of a new piece of equipment for determining the Young and shear modulus and Poisson ratio of materials was established at Imperial College London in 2013. The measurement principle is based on the relationship between shape, density and stiffness and the natural vibration frequencies of a sample. For example, for determination of the Young modulus, typically a bending vibration mode is excited by hitting a sample supported on the nodes of the vibration with a small projectile in the centre. The resulting vibration is picked up with a microphone and analysis of this signal using the Fourier transformation yields the frequency of the vibration. The software also analyses the decay in amplitude of the vibration with time to determine a value for the damping of the vibration. So, the resonant frequency and damping analyzer (RFDA), use the impulse excitation technique: A small mechanical impulse causes the sample to vibrate. The vibration depends on elastic properties, density, geometry and inner structures (lattice or fissures).

## 2.2 Electricity and magnetism

Considerations relating to electric charge dominate electricity and electronics. Electrical charges interact via a field. That field is called electric if the charge doesn't move. If the charge moves, thus realizing an electric current, especially in an electrically neutral conductor, that field is called magnetic. Electricity can give qualitatively over a potential. The electricity has a substance-like property, the electric charge. Energy (or power) in elementary electrodynamics is calculated by multiplying the potential by the amount of charge (or current) found at that potential: potential times charge. The electric force acting on a point charge  $q_1$  as a result of the presence of a second point

charge  $q_2$  is given by Coulomb's Law as:  $F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$ , where  $\epsilon_0$  is permittivity of the space. The

electric charge obey a conservation law. Gauss's law is a general law applying to any closed surface. It is an important tool since it permits the assessment of the amount of enclosed charge by mapping the field on a surface outside the charge distribution. Electric current, voltage, electric resistance, conductance, electric capacitance, inductance, energy carried by electricity and power are main physical quantities that can be measured by already known classical devices. Operation of these devices is based on the fundamental laws of classical electrodynamics described by classical Maxwell's equations, from which can perform laws like: 1) First Gauss' law of electricity, 2) II Gauss' law of magnetism, 3) III. Faraday' law of inductivity and 4) IV. Amper's law. Electric field can be measured by field meter, but magnetic field can be measured by compass, Hall effect sensor, magnetometer and SQUID. A SQUID (superconducting quantum interference device) is a very sensitive magnetometer used to measure extremely subtle magnetic fields, based on superconducting loops containing Josephson junctions. SQUID operating is based on the Josephson effect [7].

### - Hall Effect – short description

If charges flow (thus establishing an electric current) through a conductor in a magnetic field, the magnetic field exerts a transverse force on the moving charges which tends to push them to one side of the conductor. This is most evident in a thin flat conductor as illustrated on figure 1. A buildup of charges at the sides of the conductors will continue until it balances the magnetic influence, producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall effect. The direction of the current  $I$  in the diagram is that of conventional currents, so that the motion of electrons is in the opposite direction. That further confuses all the „right-hand-rule“ manipulations you have to go through to get the direction of the forces.

The Hall voltage is given by  $V_H = \frac{IB}{ned}$ , where  $n$  is density mobile charges, and  $e$  electron charge.

The Hall effect can be used to measure magnetic fields with a Hall probe, power of electric current, angular torque of electric engine and electric current in conductor without contact. Furthermore, two Nobel prizes (1985, 1998) were awarded to the Hall effect discoveries (classical and quantum). The

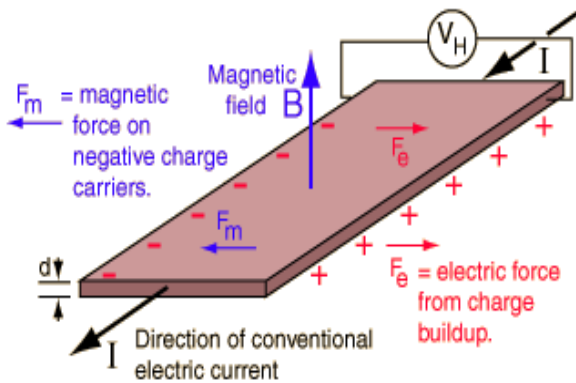


Figure 1. Schetch for Hall effect (Credit: [7])

basic physical principle underlying the Hall effect is the Lorentz force, which is a combination of two separate forces: the electric force and the magnetic force. When an electron moves along the electric field direction perpendicular to an applied magnetic field, it experiences a magnetic force  $-q\vec{v} \times \vec{B}$  acting normal to both directions. Lorentz force  $\vec{F}$  is therefore equal to  $-q(\vec{E} + \vec{v} \times \vec{B})$ , where  $q$  is the elementary charge,  $\vec{E}$  is the electric field,  $\vec{v}$  is the particle velocity, and  $\vec{B}$  is the magnetic field.

### 2.3. Thermodynamics

Thermodynamics is a branch of physics concerned with heat and temperature and their relation to energy and work. It defines macroscopic variables, such as internal energy, entropy, and pressure that partly describe a body of matter or radiation. It states that the behavior of those variables is subject to general constraints, that are common to all materials, not the peculiar properties of particular materials. These general constraints are expressed in the four laws of thermodynamics. Thermodynamics describes the bulk behavior of the body, not the microscopic behaviors of the very large numbers of its microscopic constituents, such as molecules.

Temperature measurement is based on the following phenomena /physical principles/:

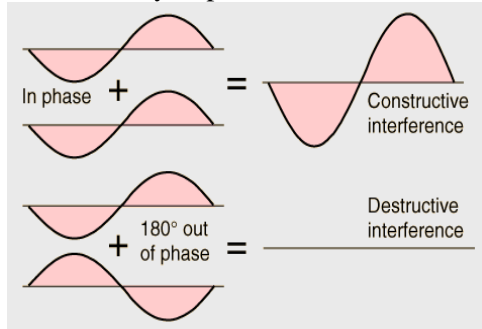
Electromagnetic spectroscopy [It is study of the interaction between matter and radiated energy. It originated through the study of visible light dispersed according to its wavelength, e.g., by a prism. The concept was expanded to comprise any interaction with radiative energy as a function of its wavelength or frequency. The data are often represented by a spectrum, a plot of the response of interest as a function of wavelength]; different types of thermometers operating principles [Galileo; gas thermometer principle: relation between temperature and volume or pressure of a gas – Gas laws; constant pressure and constant volume gas thermometer; liquid crystal thermometer; Liquid thermometer principle: relation between temperature and volume of a liquid; Alcohol and Mercury-in-glass thermometer; Pyrometers principle: temperature dependence of spectral intensity of light (Planck's law), i.e. the color of the light relates to the temperature of its source, measurement of thermal radiation (instead of thermal conduction, or convection) means: Resistance thermometer principle: relation between temperature and electrical resistance of metals, usually platinum; solid thermometer principles: relation between temperature and length of a solid (Coefficient of thermal expansion) Bi-metallic strip; Thermistors principle: relation between temperature and electrical resistance of ceramics or polymers, Thermocouples principle: relation between temperature and voltage of metal junctions (Seebeck effect), Triple Point cell used for calibrating thermometers].

### 2.4. Oscillations, waves and optics

This area covers the processes like oscillations, propagation of waves, light waves, reflection, refraction, interference, diffraction and polarization. This also includes sound, compression waves in matter, sound pressure, sound intensity, hearing, and loudness. The wave phenomena and optics did left the biggest mark on the development of measurement techniques. Photonics, fiberoptics, interferometry, diffraction, thermovision and laser techniques are in the field of advanced physics and phenomena that have experienced the greatest growth and expansion in modern technology and measurement' techniques at all.

## - Interferometry

The phenomena related to electromagnetic waves and light have complex consequences for many processes. The mathematics behind ELM descriptions, Maxwell's equations, are very belaboring and strenuous. A lot about the way we think of light in a wave form, just as electromagnetic wave, however, comes from Huygen's Principle of 1678. His principle states that "all points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, which propagate outward with speeds characteristic of waves in that medium"[4]. This principle becomes very important for diffraction analysis.



In order to understand interferometry, we need to understand interference. Interference happens when two waves carrying energy meet up and overlap. The energy they carry gets mixed up together so, instead of two waves, you get a third wave whose shape and size depends on the patterns of the original two waves. When waves combine like this, the process is called superposition. Superposition of the coherent waves (waves with constant phase difference) results in phenomena called interference. When the waves get to the walls, they bounce back off the hard

surface more or less unchanged in size but with their velocity reversed. Each wave reflects off the tub just as if you'd kicked a rubber ball at the wall. Once the waves come back to where your hand is, you can make them much *bigger* by moving your hand in step with them. In effect, you create new waves that add themselves to the original ones and increase their amplitude. When waves add together to make bigger waves, scientists call it constructive interference. If you move your hands a different way, you can create waves that are out of step with your original waves. When these new waves add to the originals, they subtract energy from them and make them smaller. This is what scientists call

destructive interference. Constructive interference means combining two or more waves to get a third wave that's bigger. The new wave has the same wavelength and frequency but more amplitude (higher peaks). Destructive interference means waves subtracting and canceling out. The peaks in one wave are canceled by the troughs in the other. The extent to which one wave is in step with another is known as its phase. Adding two waves like this creates a third wave that has an unusual, rising and falling pattern of peaks and troughs. Shine a wave like this onto a screen and you get a characteristic pattern of light and dark areas called interference fringes. This pattern is what you study and measure with an interferometer. First interferometer (historical known) was Michelson's interferometer (Figure 2.)

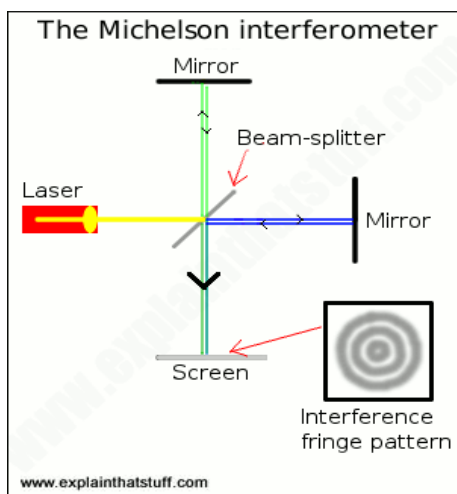


Figure 2. Sketch of Michelson's interferometer

The basic idea of interferometry involves taking a beam of light (or another type of electromagnetic radiation) and splitting it into two equal halves using what's called a beam-splitter. This is simply a piece of glass whose surface is very thinly coated with silver. If you shine light at it, half the light passes straight through and half of it reflects back - so the beam-splitter is like a cross between an ordinary piece of glass and a mirror. One of the beams (known as the reference beam) shines onto a mirror and from there to a screen or camera. The other beam shines at or through something you want to measure, onto a second mirror, back through the beam splitter, and onto the same screen or camera. This second beam travels an extra distance (or in some other slightly different way) to the first beam, so it gets slightly out of step (out of phase). When the two light beams meet up at the screen or camera, they overlap and interfere, and the phase difference between them creates a pattern of light and dark areas (in other words, a set of interference fringes). The light areas are places where the two beams have added together (constructively) and become brighter; the dark areas are places where the beams have subtracted from one another (destructively). The exact pattern of interference depends on the different way or the extra distance that one of the beams has traveled. By inspecting and

measuring the fringes, it is possible to make an exact measurement of whatever it trying to find. Most modern interferometers use laser light because it produces coherent beams. Interferometers are widely used in all kinds of scientific and engineering applications for making accurate measurements. By scanning interferometers over objects, one can also make very precise maps of surfaces [3].

## 2.5 Quantum physics - Rays ("waves" and "particles"), atomic and nuclear physics

This field of modern physics covers the phenomena related to the light and radiation, electromagnetic spectrum, cathode – X- ray, atom polarization and electron polarization, ionizing radiation.

### 2.5.1 Laser – Physical principles of operating

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. It creates a narrow and low-divergent beam of coherent light, while most other light sources emit incoherent light, which has a phase that varies randomly with time and position. Most lasers emit nearly "monochromatic" light with a narrow wavelength spectrum

The principle of a laser is based on three separate physical phenomena: a) stimulated emission within an amplifying medium, b) population inversion of electrons and c) an optical resonator. According to the quantum mechanics, an electron within an atom or lattice can have only certain values of energy, or energy levels. There are many energy levels that an electron can occupy, but here we will only consider two. If an electron is in the excited state with the energy  $E_2$  it may spontaneously goes to the ground state, with energy  $E_1$ , releasing the difference in energy between the two states as a photon. (see Figure 3.) This process is called spontaneous emission, producing fluorescent light. The phase and direction of the photon in spontaneous emission are completely random due to Heisenberg

uncertainty principle. The angular frequency  $\omega$  and energy of the photon is:  $E_2 - E_1 = \hbar \omega$ , where  $\hbar$  is the reduced Planck's constant. On the other hand, a photon with a particular frequency satisfying that energy relation would be absorbed by an electron in the ground state.

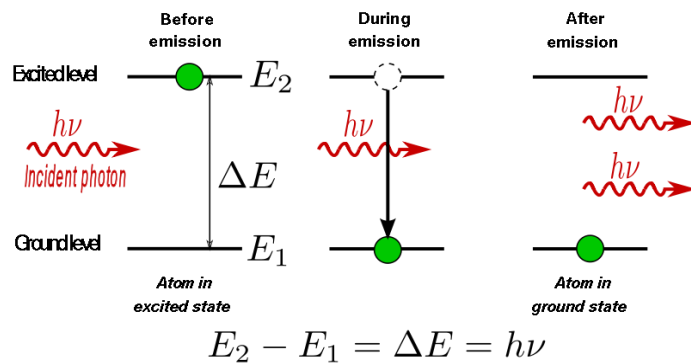


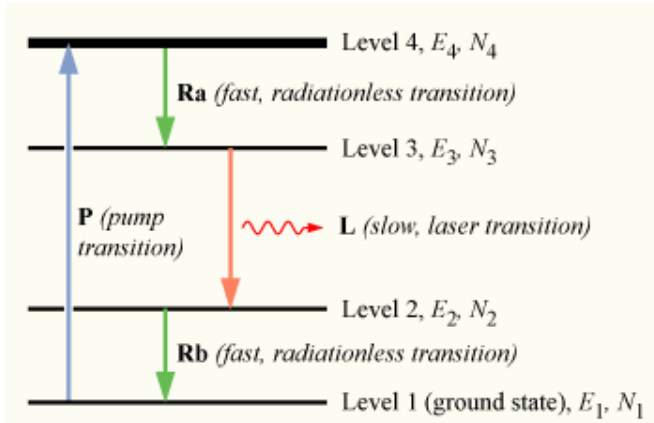
Figure 3. Spontaneous and stimulated emission diagram  
ometer

The electron remains in this excited state for a period of time typically less than one microsecond. Then it returns to the lower state spontaneously by a photon or a phonon. These common processes of absorption and spontaneous emission cannot give rise to the amplification of light. The best that can be achieved is that for every photon absorbed, another is emitted.

Alternatively, if the excited-state atom is perturbed by the electric field of a photon with frequency  $\omega$ , it may release a second photon of the same frequency, in phase with the first photon. The atom

will again go into the ground state. This process is known as stimulated emission. (Figure 3.) The emitted photon is identical to the stimulating photon with the same frequency, polarization, and direction of propagation. And there is a fixed phase relationship between light radiated from different atoms. The photons, as a result, are totally coherent. This is the critical property that allows optical amplification to take place. All the three processes occur simultaneously within a medium. However, in thermal equilibrium, stimulated emission does not account to a significant extent. The reason is there are far more electrons in the ground state than in the excited states. And the rates of absorption and emission is proportional the number of electrons in ground state and excited states, respectively. So absorption process dominates. If the higher energy state has a greater population than the lower energy state, then the light in the system undergoes a net increase in intensity. And this is called population inversion. But this process cannot be achieved by only two states, because the electrons will eventually reach equilibrium with the de-exciting processes of spontaneous and stimulated emission. Instead, an indirect way is adopted, with three energy levels ( $E_1 < E_2 < E_3$ ) and energy population  $N_1$ ,  $N_2$  and  $N_3$  respectively. (Figure 4.) In a medium suitable for laser operation, we require these excited atoms to quickly decay to level 2, transferring the energy to the phonons of the lattice of

the host material. This wouldn't generate a photon, and labeled as R, meaning radiationless. Then electrons on level 2 will jump by spontaneous emission to level 1, labeled as L, meaning laser. If the life time of L is much longer than that of R, the population of the  $E_3$  will be essentially zero and a population of excited state atoms will accumulate in level 2. When level 2 hosts over half of the total electrons, a population inversion be achieved.



with energy slightly above the band gap energy can

Figure 4. Electron transitions within 3 and 4-level gain medium (Credit:[5])

excite electrons into a higher state in the conduction band, from where they quickly decay to states near the bottom of the conduction band. But, the holes generated in the valence band move to the top of the valence band. Electrons in the conduction band can then recombine with these holes, emitting photons with an energy near the band gap energy. (Figure 5.)

Although with a population inversion is possible to amplify a signal via stimulated emission, the overall single-pass gain is quite small, and most of the excited atoms in the population emit spontaneously and do not contribute to the overall output. Then the resonator is applied to make a positive feedback mechanism. An optical resonator, as main part of laser, usually has two flat or concave mirrors, one on either end, that reflect lasing photons back and forth so that stimulated emission continues to build up more and more laser light. Photons produced by spontaneous transition in other directions are off axis so that they won't be amplified to compete with stimulated emission on axis. There may be many laser transitions contribute in the laser, because of the band in solids or molecule energy levels of organics. Optical resonator also has a function of wavelength selector. It just make a standing wave condition for the photons:  $L = n\lambda/2$ , where L is the length of resonator, n is some integer and  $\lambda$  is the wavelength. Only wavelengths satisfying this equation will get resonated and amplified. The output of a laser may be a continuous constant-amplitude output (known as CW), or pulsed, by using the techniques of Q-switching, model-locking, or gain-switching [5].

### 3. SENSORS

Sensors are sophisticated device that are frequently used to detect and respond to electrical or optical signals. A sensor is converter that measures a physical quantity or parameter (for example: temperature, blood pressure, humidity, speed, etc.) and converts it into a signal which can be read by an observer or by an (today mostly electronic) instrument. For example, a mercury-in-glass thermometer converts the measured temperature into expansion and contraction of a liquid which can be read on a calibrated glass tube. A thermocouple converts temperature to an output voltage which can be read by a voltmeter. The physical background of sensor's technology covers almost all the physics area, from mechanics to the advanced quantum physics.

Sensors are used for a wide range of functions in automated systems, such as to measure pressure, force and distance, detect the presence and/or position of work pieces and the completion of process steps. This part of lecture gives an overview of sensor technology based on physics and physical

Because half of the electrons must be excited, the pump system need to be very strong. This makes three-level lasers rather inefficient. Most of the present lasers are 4-level lasers, see Figure 5. The population of level 2 and 4 are 0 and electrons just accumulate in level 3. Laser transition takes place between level 3 and 2, so the population is easily inverted. In semiconductor lasers, where there are no discrete energy levels, a pump beam

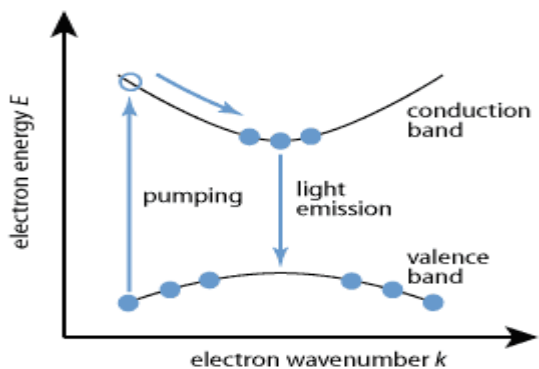


Figure 5. Diagram of electron transitions in semiconductor gain medium (Credit:[5])

processes, function of different types of sensors (selected). Sensors are used in everyday objects such as touch-sensitive elevator buttons and lamps which dim or brighten by touching the base. There are also innumerable applications for sensors of which most people are never aware. Applications include cars, machines, aerospace, medicine, manufacturing and robotics.

A sensor's sensitivity indicates how much the sensor's output changes when the measured quantity changes. For instance, if the mercury in a thermometer moves 1 cm when the temperature changes by 1°C, the sensitivity is 1 cm/°C (it is basically the slope  $dy/dx$  assuming a linear characteristic). Sensors that measure very small changes must have very high sensitivities. Sensors also have an impact on what they measure; for instance, a room temperature thermometer inserted into a hot cup of liquid cools the liquid while the liquid heats the thermometer. Sensors need to be designed to have a small effect on what is measured; making the sensor smaller often improves this and may introduce other advantages. Technological progress allows more and more sensors to be manufactured on a microscopic scale as microsensors using MEMS technology. In most cases, a microsensor reaches a significantly higher speed and sensitivity compared with macroscopic approaches [12].

### 3.1 Classification of Sensors:

The sensors are classified into the following criteria: 1. Primary Input quantity (Measurand); 2. Transduction principles (Using physical and chemical effects); 3. Material and Technology; 4. Property and 5. Application.

Transduction principle is the fundamental criteria which are followed for an efficient approach. Usually, material and technology criteria are chosen by the development engineering group.

Classification based on property is given below:

- Temperature - Thermistors, thermocouples, RTD's, IC and many more.
- Pressure - Fiber optic, vacuum, elastic liquid based manometers, LVDT, electronic.
- Flow - Electromagnetic, differential pressure, positional displacement, thermal mass, etc.
- Level Sensors - Differential pressure, ultrasonic radio frequency, radar, thermal displacement.
- Proximity and displacement - LVDT, photoelectric, capacitive, magnetic, ultrasonic.
- Biosensors - Resonant mirror, electrochemical, surface Plasmon resonance, Light addressable potentiometric
- Image - Charge coupled devices, CMOS
- Gas and chemical - Semiconductor, Infrared, Conductance, Electrochemical.
- Acceleration - Gyroscopes, Accelerometers.
- Others - Moisture, humidity sensor, Speed sensor, mass, Tilt sensor, force, viscosity.

Surface Plasmon resonance and Light addressable potentiometer from the Bio-sensors group are the new optical technology based sensors. Accelerometers are independently grouped because of their vital role in future applications like aircraft, automobiles, etc and in fields of videogames, toys, etc. Magnetometers are those sensors which measure magnetic flux intensity.

- **Surface plasmons (SPs)** are coherent electron oscillations that exist at the interface between any two materials where the real part of the dielectric function changes sign across the interface (e.g. a metal-dielectric interface, such as a metal sheet in air). SPs have lower energy than bulk (or volume) plasmons which quantize the longitudinal electron oscillations about positive ion cores within the bulk of an electron gas (or plasma). The charge motion in a surface plasmon always creates electromagnetic fields outside (as well as inside) the metal. The *total* excitation, including both the charge motion and associated electromagnetic field, is called either a surface plasmon polariton at a planar interface, or a localized surface plasmon for the closed surface of a small particle.

The existence of surface plasmons was first predicted in 1957 by Rufus Ritchie [10]. Information transfer in nanoscale structures, similar to photonics, by means of surface plasmons, is referred to as plasmonics [7].

Classification of sensors based on application is next: i) Industrial process control, measurement and automation; ii) Non-industrial use—aircraft, medical products, automobiles, consumer electronics, other type of sensors.

Classification based on power or energy supply requirement of the sensors: i) Active sensor - Sensors that require power supply are called as active sensors. Example: LiDAR (Light detection and ranging), photoconductive cell.

ii) Passive sensor - Sensors that do not require power supply are called as passive sensors. Example: Radiometers, film photography.



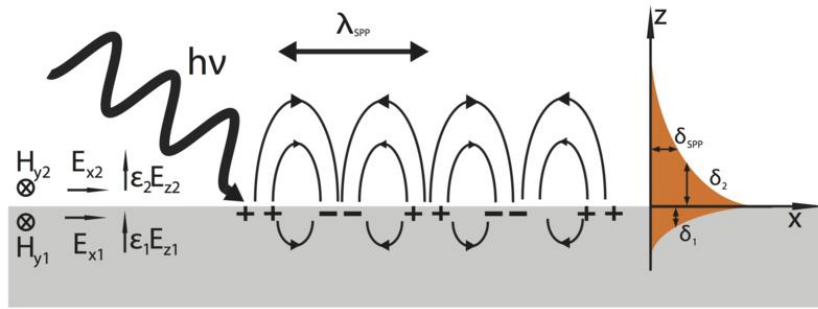


Figure 6. Schematic representation of an electron density wave propagating along a metal – dielectric interface. The charge density oscillations and associated electromagnetic fields are called surface plasmon – polariton waves. The exponential dependence of the electromagnetic field intensity on the distance away from the interface is shown on the right. These waves can be excited very efficiently with light in the visible range of the electromagnetic spectrum. (Credit: [9])

There are several group of sensors, like 1) Accelerometers /based on the micro electro mechanical sensor technology and used for patient monitoring which includes pace makers and vehicle dynamic systems; 2) Biosensors /based on the electrochemical technology, used for food testing, medical care device, water testing, and biological warfare agent detection; 3) Image Sensors /based on the CMOS technology, used in electronics, biometrics, traffic and security surveillance and PC imaging.

### 3.2 Sensor Technology based on physics and physical phenomena

**- Piezoelectric effect basics:** A piezoelectric substance is one that produces an electric charge when a mechanical stress is applied (the substance is squeezed or stretched). Conversely, a mechanical deformation (the substance shrinks or expands) is produced when an electric field is applied. This effect is formed in crystals that have no center of symmetry. To explain this, look at the individual molecules that make up the crystal. Each molecule has a polarization. They form a dipole. This is a result of the atoms that make up the molecule and the way the molecules are shaped. In a monocrystal the polar axes of all of the dipoles lie in one direction, so the crystal is said to be symmetrical. In a polycrystal, there are different regions within the material that have a different polar axis. It is asymmetrical. In order to produce the piezoelectric effect, the polycrystal is heated under the application of a strong electric field. The heat allows the molecules to move more freely and the electric field forces all of the dipoles in the crystal to line up and face in nearly the same direction (Figure 7). The piezoelectric effect can now be observed in the crystal. If the material is compressed, then a voltage of the same polarity as the poling voltage will appear between the electrodes. If stretched, a voltage of opposite polarity will appear. Conversely, if a voltage is applied the material will deform. A voltage with the opposite polarity as the poling voltage will cause the material to expand, and a voltage with the same polarity will cause the material to compress. If an AC signal is applied then the material will vibrate at the same frequency as the signal.

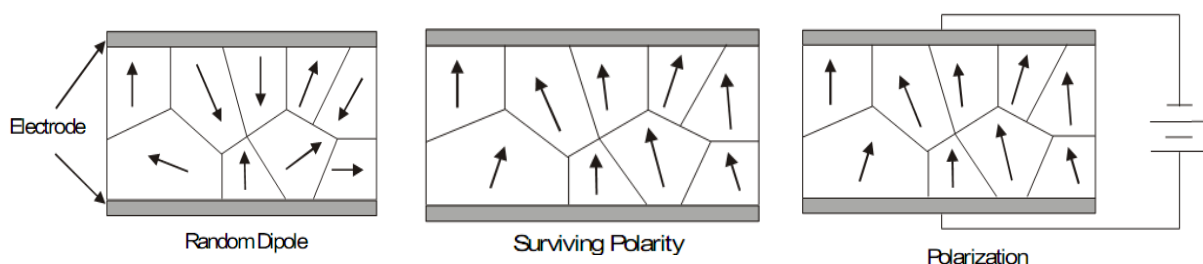


Figure 7. Polarization of Ceramic Material to Generate Piezoelectric Effect (Credit: [11])

The piezoelectric crystal bends in different ways at different frequencies. This bending is called the vibration mode. The crystal can be made into various shapes to achieve different vibration modes. An important group of piezoelectric materials are ceramics [11]. Piezoelectric sensors operate on the principle of piezoelectric effect. By this effect the mechanical energy converts into electricity and vice versa. The piezoelectric effect is reversible process.

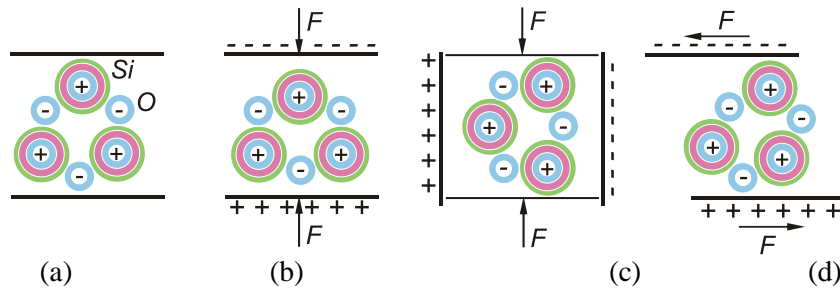


Figure 8. Piezoelectric effect at quartz, (a) unstressed crystal (b), (c), (d) generation of electricity at various load conditions

Some piezoelectric materials in naturally occurring are -Quartz -Cane sugar -Collagen-Topaz -DNA - Rochelle salt -Wood -many many others -Tendon. Man-made ceramics like - Barium titanate(BaTiO<sub>3</sub>) - Barium titanate was the first petzoelectric ceramic discovered. Most important natural piezoelectric material is SiO<sub>2</sub>-crystal quartz. When some force acts on the crystal quartz (Figure 8.) the crystal lattice will deform. This deformation causes piezoelectricity, measured by voltage on electrodes located on the crystal surface. Some simple design of piezoelectric sensors is given on Figure 9. , where they can have the shape like sheet (tape) (a), disc shape (b) , cylindric shape (c) and longitudinal cylindar segment (d)

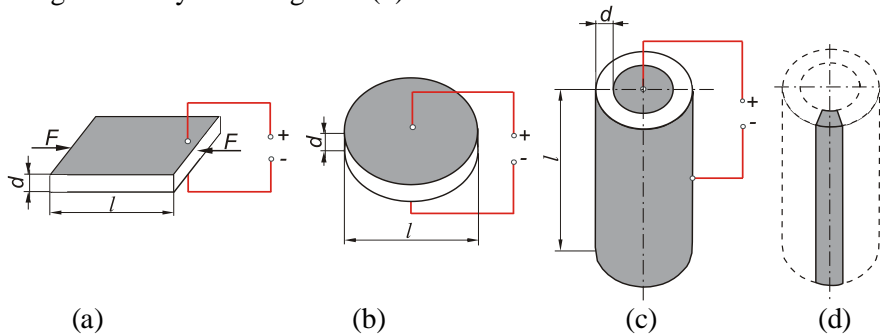


Figure 9. Simple piezoelectric sensors: (a) sheet, (b) disc, (c) cylinder, (d) longitudinal cylinder

**- Current sensor:** Measuring a voltage in any system is a “passive” activity as it can be done easily at any point in the system without affecting the system performance. However, current measurement is “intrusive” as it demands insertion of some type of sensor which introduces a risk of affecting system performance. Current measurement is of vital importance in many power and instrumentation systems. Knowing the amount of current being delivered to the load can be useful for wide variety of applications. Current sensing is used in wide range of electronic systems: Battery life indicators and chargers, current and voltage regulators, DC/DC converters, ground fault detectors, programmable current sources, linear and switch-mode power supplies, communications devices, automotive power electronics, motor speed controls and overload protection, etc. A current sensor detects and converts current to an easily measured output voltage, which is proportional to the current through the measured path. When a current flows through a wire or in a circuit, voltage drop occurs. Also, a magnetic field is generated surrounding the current carrying conductor. Both of these phenomena are made use of in the design of current sensors.

Thus, there are two types of current sensing: direct and indirect. Direct sensing is based on Ohm’s law, while indirect sensing is based on Faraday’s and Ampere’s law. Direct sensing involves measuring the voltage drop associated with the current passing through passive electrical components. Indirect sensing involves measurement of the magnetic field surrounding a conductor through which current passes. Generated magnetic field is then used to induce proportional voltage or current which is then transformed to a form suitable for measurement and/or control system. The traditional way of current sensing introduces a resistor in the path of the current to be sensed. The sense resistor can be placed in series with the inductor, switches, and the load. Thus, a current sensing resistor should be considered as a current-to-voltage converter.

**- Sensors and transducers:** Simple stand alone electronic circuits can be made to repeatedly flash a light or play a musical note, but in order for an electronic circuit or system to perform any useful task

or function it needs to be able to communicate with the “real world” whether this is by reading an input signal from an “ON/OFF” switch or by activating some form of output device to illuminate a single light. An electronic system or circuit must be able to “do” something and sensors and transducers are the perfect components for doing this. The word “Transducer” is the collective term used for both sensors which can be used to sense a wide range of different energy forms such as movement, electrical signals, radiant energy, thermal or magnetic energy etc, and actuators which can be used to switch voltages or currents. There are many different types of sensors and transducers, both analogue and digital and input and output available to choose from. The type of input or output transducer being used, really depends upon the type of signal or process being “Sensed” or “Controlled” but we can define a sensor and transducers as devices that converts one physical quantity into another. Devices which perform an “Input” function are commonly called sensors. Devices which perform an “Output” function are generally called actuators and are used to control some external device, for example movement or sound. Electrical transducers are used to convert energy of one kind into energy of another kind. For example a microphone (input device) converts sound waves into electrical signals for the amplifier to amplify (a process), and a loudspeaker (output device) converts these electrical signals back into sound waves (Figure 10).

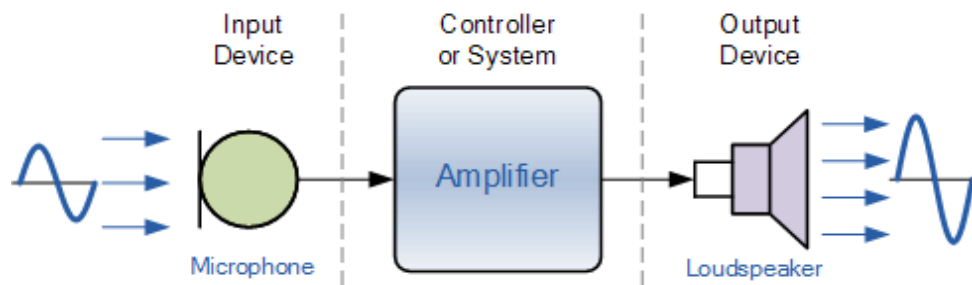


Figure 10. Simple Input/Output system using sound transducers, (Credit: [14])

Analog sensors produce a continuous output signal or voltage which is generally proportional to the quantity being measured. Physical quantities such as temperature, speed, pressure, displacement, strain etc. are all analogue quantities as they tend to be continuous in nature. Analogue sensors tend to produce output signals that are changing smoothly and continuously over time. Then circuits which measure analogue signals usually have a slow response and/or low accuracy. Also analogue signals can be converted into digital type signals for use in micro-controller systems by the use of analogue-to-digital converters (Figure 11.) [14].

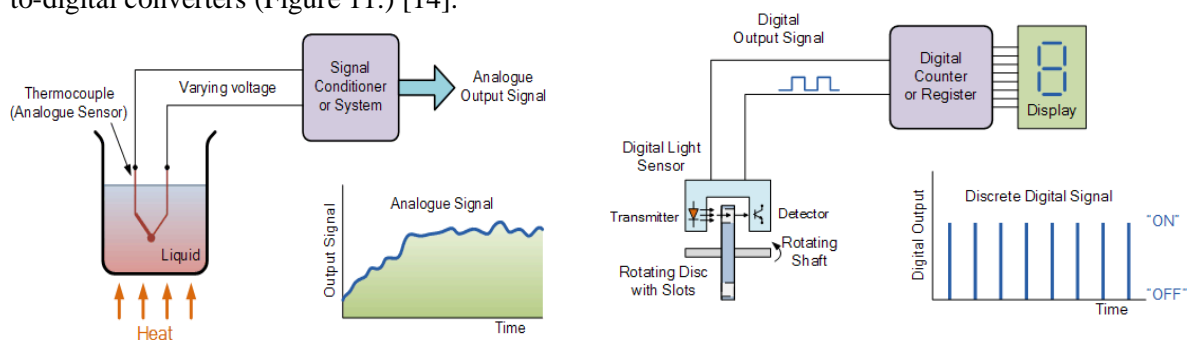


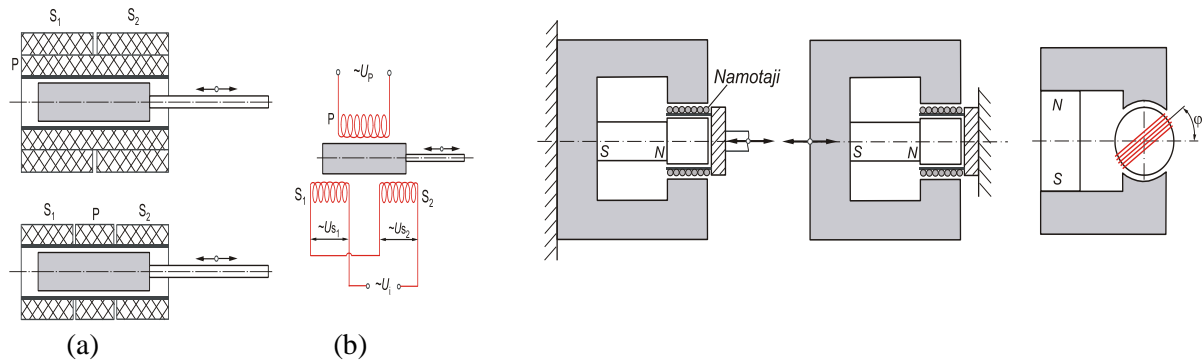
Figure 11. Left) Thermocouple used to produce an analogue signal, Right) a digital signal

- **Electromagnetic sensors:** Principle of electromagnetic sensor operating is based on the dependence of the change in inductance of solenoid electromagnetic circuits or electromagnetic induction. Because of that they can be classified into inductive which are passive sensors, and induction's which are active sensors. Both of them are operating on non-contacting principle and the sensor's mass does not influence on the measurements results.

- **Inductive sensors:** Inductance of the solenoid with a ferromagnetic core and the air gap is calculated as  $L = \mu_0 \frac{N^2 A_h}{2h}$  where  $\mu_0$  is magnetic permeability of vacuum,  $N$  number of coils,  $h$  width of gap and  $A_h$  crosssection of gap area. The magnetic quantities  $\mu_0$ ,  $N$  and magnetic circuit geometry

are changing upon the influence of mechanical quantities, and this principle of parameters variation is used for building appropriate sensor. One of the most commonly used sensors to measure the movements and other mechanical quantities is linear variable differential transformer (LVDT) sensor. LVDT sensor is like transformer with one primary (P) and two secondary ( $S_1$  i  $S_2$ ) coils, (Figure 12.), symmetrically located.

**-Induction sensors:** These sensors for transformation of non-electrical measured quantity into electrical uses the principle of electromagnetic induction. The induced voltage is equal  $U = NlvB$ .



Slika 12. LVDT sensor, (a) design (b) scheme; Right) Three types of induction sensors

**- Capacitive sensors:** Capacitive sensors are passive sensors. The principle of operation is based on their capacity to change the capacity of capacitor that is changing under the influence of the measured non-electrical quantity. The capacitor consists of two metal plates between which is a dielectric (insulating) material. Capacity is given by expression  $C = \epsilon_0 \epsilon_r \frac{A}{d}$ , where A plate area, d distance

between plates,  $\epsilon_r$  relative dielectric constant and  $\epsilon_0$  dielectric constant of vacuum. If a non-electric quantity affects the parameter change A, d or  $\epsilon_r$ , then the capacity of capacitor C will be also changed, so that is base for getting a capacitive sensor. Depending on influence of A, d or  $\epsilon_r$ , there are different types of these sensors.

**-Resistive sensors:** The working principle of resistive sensors based on the change in electrical resistance depending on the displacement action, mechanical stress or temperature.

Princip rada otporničkih senzora zasniva se na promjeni električnog otpora u zavisnosti od djelovanja pomjeranja, mehaničke sile ili temperature. The basic sensor element in this case is a resistor that can be solid, liquid or gas. Most of them are solid. [12, 13]

#### 4. SOME SELECTIVE PHYSICAL BASED MEASURING METHODS

##### 4.1 Laser Doppler Anemometry – LDA. Measurement principles of LDA

The Laser Doppler Anemometry, or LDA, also known as Laser Doppler Velocimetry (LDV), is an optical technique ideal for non-intrusive 1, 2 or 3 - dimensional point measurement of velocity and turbulence distribution in both free flows and internal flows. It is a widely accepted method - tool for fluid dynamic investigations in gases and liquids and has been used as such for more than three decades. LDA works on non-intrusive principle and directional sensitivity, what makes it very suitable for applications with reversing flow, chemically reacting or high-temperature media and rotating machinery, where physical sensors are difficult or impossible to use. It requires tracer particles in the flow. The method's particular advantages are: non-intrusive measurement, high spatial and temporal resolution, no need for calibration and the ability to measure in reversing flows.

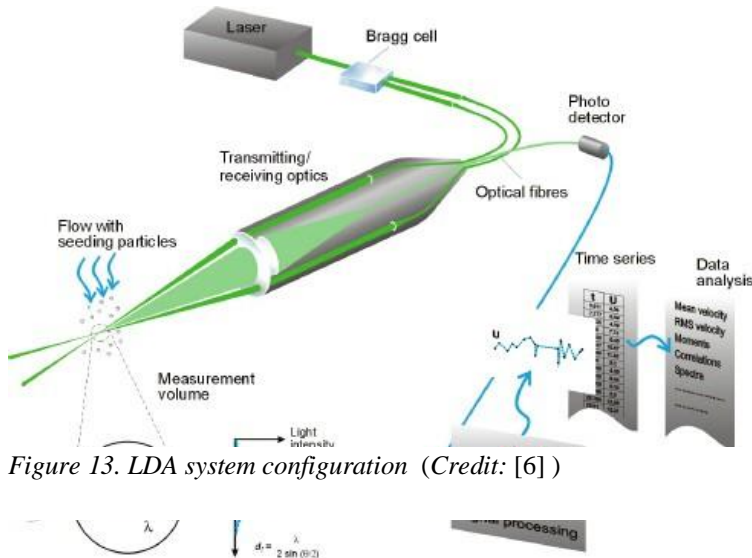


Figure 13. LDA system configuration (Credit: [6])

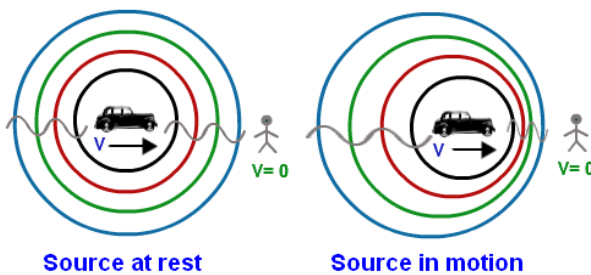
Measurement flow velocity of fluid by laser anemometry is based on detection of Doppler shift frequency of scattered light on tracers flow during motion over the measurable area.

The Doppler effect is observed whenever the source of waves is moving with respect to an observer. The Doppler effect produced by a moving source of waves in which there is an apparent upward shift in frequency for observers towards whom the source is approaching and an apparent downward shift in

frequency for observers from whom the source is receding. It is important to note that the effect does not result because of an actual change in the frequency of the source. The effect is only observed because the distance between observer (receiver) and the emitter (source) is decreasing and the distance between observer and source is increasing. The Doppler effect can be observed for any type of wave - water wave, sound wave, light wave, etc. We are most familiar with the Doppler effect because of our experiences with sound waves. Perhaps you recall an instance in which a police car or emergency vehicle was traveling towards you on the highway. As the car approached with its siren blasting, the pitch of the siren sound (a measure of the siren's frequency) was high; and then suddenly after the car passed by, the pitch of the siren sound was low. That was the Doppler effect - an apparent shift in frequency for a sound wave produced by a moving source. Doppler shift was given by Christian Johann Doppler in 1842. This apparent change in the frequency of sound as a result of relative motion between the source and the observer is the Doppler effect. There are eight Doppler effect formulas for frequency depending on cases:

(i) When the source is moving towards or away (sign + in denominator) a observer at rest

$$f' = \frac{v}{v \mp v_s} f$$



(ii) When observer is moving towards or away from the stationary source

$$f' = \frac{(v \mp v_o)}{v} f$$

(iii) When both source and observer moves towards each other

$$f' = \frac{(v - v_o)}{(v \pm v_s)} f$$

or the source is approaching the stationary observer and iv) observer

moving away from source and when the observer is approaching the stationary source

$$f' = \frac{(v + v_o)}{(v \mp v_s)} f$$

where  $v_s$  = velocity of the source,  $v_o$  = velocity of the observer,  $v$  = velocity of sound or light in medium,  $f$  = real frequency,  $f'$  = apparent frequency.

The basic configuration of an LDA consists of: i) A continuous wave laser, ii) Transmitting optics, including a beam splitter and a focusing lens, iii) Receiving optics, comprising a focusing lens, an interference filter and photodetector and iv) A signal conditioner and a signal processor. Advanced systems may include traverse systems and angular encoders. A Bragg cell is often used as the beam splitter. It is a glass crystal with a vibrating piezo-crystal attached. The vibration generates acoustical waves acting like an optical grid. The output of the Bragg cell is two beams of equal intensity with frequencies  $f_0$  and  $f_{shift}$ . These are focused into optical fibres bringing them to a probe. In the probe, the parallel exit beams from the fibres are focused by a lens to intersect in the probe volume [6]. The light intensity is modulated due to interference between the laser beams. This produces parallel planes of high light intensity, so called fringes. The fringe distance  $d_f$  is defined by the wavelength of the laser

light and the angle between the beams:  $d_f = \frac{\lambda}{2 \sin(\theta/2)}$ . Each particle passage scatters light

proportional to the local light intensity. Flow velocity information comes from light scattered by tiny "seeding" particles carried in the fluid as they move through the probe volume. The scattered light contains a Doppler shift, the Doppler frequency  $f_D$ , which is proportional to the velocity component perpendicular to the bisector of the two laser beams, which corresponds to the  $x$  axis shown in the probe volume. The scattered light is collected by a receiver lens and focused on a photo-detector. The photo-detector converts the fluctuating light intensity to an electrical signal, the Doppler burst, which is sinusoidal with a Gaussian envelope due to the intensity profile of the laser beams. The Doppler bursts are filtered and amplified in the signal processor, which determines  $f_D$  for each particle, using the robust Fast Fourier Transform (FFT) algorithm. The fringe spacing,  $d_f$  provides information about the distance travelled by the particle. The Doppler frequency  $f_D$  provides information about the time:  $t = 1/f_D$ , while velocity is  $v = d_f \cdot f_D$ . The frequency shift obtained by the Bragg cell makes the fringe pattern move at a constant velocity. Particles which are not moving will generate a signal of the shift frequency  $f_{\text{shift}}$ . The velocities  $U_{\text{pos}}$  and  $U_{\text{neg}}$  will generate signal frequencies  $f_{\text{pos}}$  and  $f_{\text{neg}}$ , respectively. LDA systems without frequency shift cannot distinguish positive and negative flow direction, but LDA systems with frequency shift can do it. [6]

#### 4.2. Particle Image Velocimetry – PIV. Measurement principles of PIV

Particle Image Velocimetry (PIV) is a whole-flow-field technique providing instantaneous velocity vector measurements in a cross-section of a flow. Two velocity components are measured, but use of a stereoscopic approach permits all three velocity components to be recorded, resulting in instantaneous 3D velocity vectors for the whole area. The use of modern digital cameras and dedicated computing hardware, results in real-time velocity maps. This measurement method measures the velocities of micron-sized particles following the flow, where all three components may be obtained. In PIV, the velocity vectors are derived from subsections of the target area of the particle-seeded flow by measuring the movement of particles between two light pulses:  $\bar{v} = \Delta \bar{x} / \Delta t$

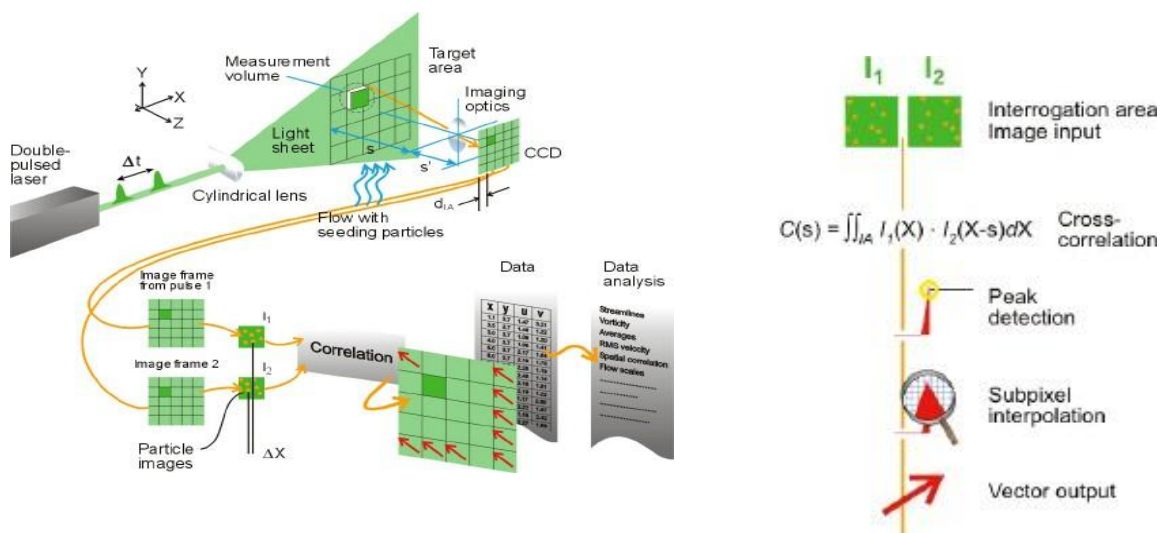


Figure 14. Left: Sketch of PDA; Right: The correlation of the two interrogation areas,  $I_1$  and  $I_2$ , results in the particle displacement  $DX$ , represented by a signal peak in the correlation  $C(DX)$

The flow is illuminated in the target area with a light sheet. The camera lens images the target area onto the sensor array of a digital camera. The camera is able to capture each light pulse in separate image frames. Once a sequence of two light pulses is recorded, the images are divided into small subsections called interrogation areas (IA). The interrogation areas from each image frame,  $I_1$  and  $I_2$ , are cross-correlated with each other, pixel by pixel. The correlation produces a signal peak, identifying the common particle displacement,  $DX$ . A velocity vector map over the whole target area is obtained by repeating the cross-correlation for each interrogation area over the two image frames

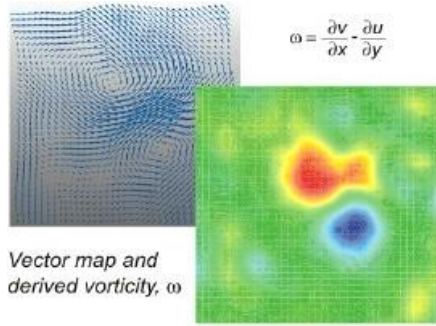


Figure 15. Double-pulsed particle images (Credit: [6])

captured by the camera. (Figure 14.) PIV images are visual, just follow the seeding. Recording both light pulses in the same image frame to track the movements of the particles gives a clear visual sense of the flow structure. The number of particles in the flow is of some importance in obtaining a good signal peak in the cross-correlation. When the size of the interrogation area, the magnification of the imaging and the light-sheet thickness are known, the measurement volume can be defined. In normal PIV systems, the third velocity component is "invisible" due to the geometry of the imaging. This third velocity component can be derived by using two cameras in a stereoscopic arrangement.

### 4.3. Particle Doppler Anemometry – PDA. Measurement principles of PDA

PDA measurements are performed on single particles, allowing for detailed analysis of particulate flows. The distribution of statistical size and velocity moments in a flow field can be measured, as well as particle concentration and local size-velocity correlation. Movement of the measurement point in the flow allows mapping of entire flow fields. The underlying principle of phase Doppler anemometry is based on light-scattering interferometry and therefore requires no calibration.

The measurement point is defined by the intersection of two focused laser beams and the measurements are performed on single particles as they move through the sample volume. Particles thereby scatter light from both laser beams, generating an optical interference pattern. A receiving optics placed at a well-chosen off-axis location projects a portion of the scattered light onto multiple detectors. Each detector converts the optical signal into a Doppler burst. The phase shift between the Doppler signals from different detectors is a direct measure of the particle diameter. The PDA technique is an extension of LDA and is based upon phase Doppler principles. Two or more detectors collect the light scattered by single particles passing through the measurement volume.

The phenomena of light scattering can be visualised by ray tracing. The light which is incident on e.g. a water droplet is partially reflected from the surface and partially transmitted and refracted in both forward and backward directions after one internal reflection. The scattered light intensity depends on the relative refractive index. Particle velocity  $U$  is calculated from the Doppler frequency  $f_D$  of the signal from any one of the detectors:

$$U = \frac{\lambda}{2 \sin(\theta/2)} f_D$$

The particle size  $D$  is derived from the phase difference between the signals from two detectors. If light scattering is dominated by reflection:

$$\Phi = \frac{2\pi D}{\lambda} \frac{\sin \theta \sin \Psi}{\sqrt{2(1 + \cos \theta \cos \Psi \cos \varphi)}} \quad \text{If it is dominated by refraction:}$$

$$\Phi = \frac{2\pi D}{\lambda} \frac{n_{rel} \sin \theta \sin \Psi}{\sqrt{2(1 + \cos \theta \cos \Psi \cos \varphi)(1 + n_{rel}^2 - n_{rel} \sqrt{2(1 + \cos \theta \cos \Psi \cos \varphi)})}}$$

The maximum particle size that can be unambiguously measured with two detectors corresponds to a phase shift of  $\Phi_{1,2} = 360^\circ$ . Reducing the distance between the detectors can extend the particle size range. This however, will also reduce the measurement resolution. Using three detectors provides both a large measurable size range ( $\Phi_{1,3}$ ) and a high measurement resolution ( $\Phi_{1,2}$ ). [6, 8]

### 4.4. Constant Temperature Anemometry (CTA) – Hot-Wire Anemometry – Thermal Anemometry. Measurement principles of CTA

Constant Temperature Anemometry – CTA, also known as Thermal Anemometry is a measurement technique well suited for the study of fine structures in turbulent flows in 1,2 or 3-dimensional gas and liquid flows, using hot-wire or hot-film probes inserted in the flow.

The working principle is based on the cooling effect of a flow on a heated body. The CTA measures velocity at a point and provides continuous velocity time series, which can be processed into amplitude and time-domain statistics. Examples are mean velocity, turbulence intensity, higher order moments, auto-correlations and power spectra. CTA is particularly suitable for the measurement of flows with very fast fluctuations at a point (high turbulence) and the study of flow

micro structures, where there is a need to resolve small flow eddies down to the order of tenths of a millimeter.

- Heat transfer from cylinders: Convective heat transfer  $Q$  from a wire is a function of the velocity  $U$ , the wire over-temperature  $T_w - T_0$  and the physical properties ( $k, \rho, \mu$ ) of the fluid. The basic relation between  $Q$  and  $U$  for a wire placed normal to the flow was suggested by L.V. King (1914). In its simplest form it reads:  $Q = (T_w - T_0) A_w h = A + BU^n$  ;  $n \approx 0,5$  , where  $A_w$  is the wire surface area and  $h$  the heat transfer coefficient, which are merged into the calibration constants  $A$  and  $B$ .

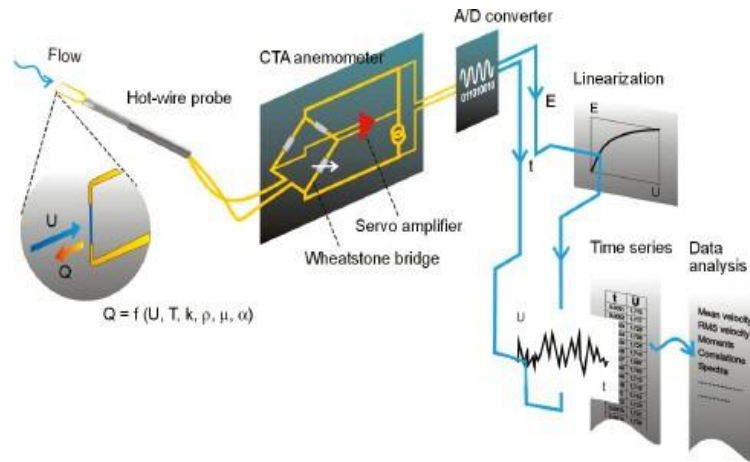


Figure16. CTA System configuration (Credit: [6])

The wire,  $R_w$ , is connected to one arm of a Wheatstone bridge (Figure 17.) and heated by an electrical current. A servo amplifier keeps the bridge in balance by controlling the current to the sensor so that the resistance - and hence temperature - is kept constant, independent of the cooling imposed by the fluid. The bridge voltage,  $E$ , represents the heat transfer and is thus a direct measure of the velocity. The combination of the sensor's low thermal inertia and the high gain of the servo loop amplifier give a very fast response to fluctuations in the flow.

Velocity sensitivity - The relation between bridge voltage and velocity may be described as an exponential function or as a polynomial:

$$E^2 = (T_w - T_0)(A + BU^{0,5}) \quad \text{or} \quad U = C_0 + C_1 E + C_2 E^2 + C_3 E^3 + C_4 E^4 + C_5 E^5$$

The relative velocity sensitivity,  $(1/U \cdot dE/dU)$  is almost constant over a wide velocity range. Calibration in a known flow forms the basis for the curve fit used to convert probe voltages into velocities (linearization).

Directional sensitivity - As a wire is sensitive to both flow velocity and direction, orthogonally arranged wires give information about both. The effective cooling velocity for a wire in a three-dimensional flow can be expressed as:  $U_{eff}^2 = U_x^2 + k^2 U_y^2 + h^2 U_z^2$ .

For 2- and 3-wire probes, the effective cooling velocity equations can be solved to provide the velocity components. The pitch and yaw factors  $k$  and  $h$  are determined by a directional calibration. Temperature sensitivity - The bridge voltage depends on both velocity and temperature. The voltage may be corrected before linearization, using the ratio between the over-temperatures during calibration and measurement. Thermal anemometry is very popular technique as it involves the use of very small probes that offer very high spatial resolution and excellent frequency response characteristics.



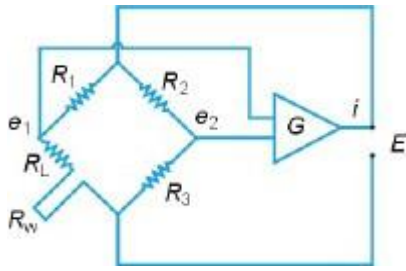


Figure 17. CTA principles scheme and probes

## 5. NANOTECHNOLOGY

### 5.1 Atomic force microscopy

Atomic force microscopy (AFM) is part of the family of techniques known as scanning probe microscopy, an extremely valuable and versatile investigative tool. An everyday example of scanning probe technique is reading the Braille alphabet—blind person moves fingers (sensitive probes) in a scanning fashion over the surface of paper (sample), looking for changes in friction or elevation of paper to detect a symbol. [17, 20]

Similar principle is used in AFM: a probe consisting of a cantilever (a long beam) and a sharp tip is brought very close to the surface of the sample. There are number of interactions between the sharp tip and sample when they are close, but the strongest ones are the Coulomb's strong, short range repulsive force (from electron clouds of tip and sample), and van der Waals interactions—longer range attractive force, (from redistribution of nearby electron clouds) which induces temporary electric dipoles attracting each other.

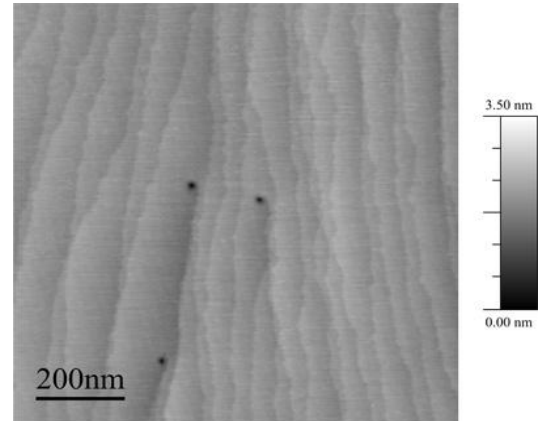


Figure 18: AFM image of the surface of a thin film of GaN. Distance between “terraces” and “steps” in the image is 0.25nm, corresponding to a single layer of GaN atoms. Credit: University of Cambridge

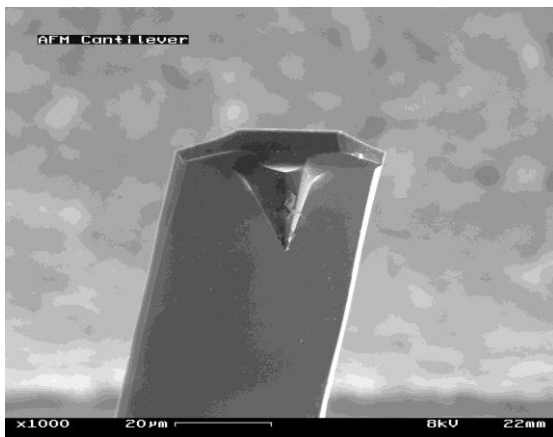


Figure 19. AFM tip under 1000x magnification

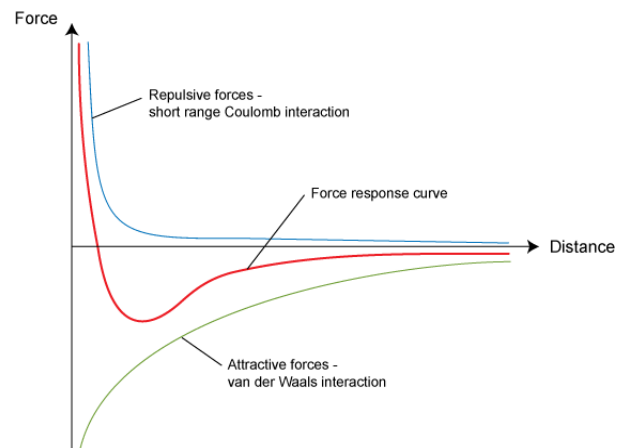


Figure 20. Force distance graph for tip-sample interaction

Combination of these interactions results in a force - distance curve similar to the one shown on Figure 20. This force will bend the cantilever, just like a load bends a long beam. In which way the beam will bend depends on the way measurement is done: e.g. in the contact mode, tip is put in

contact with the sample, which means that repulsive Coulomb's interaction dominates, and the end of cantilever bends upwards.

This force will bend the cantilever, just like a load bends a long beam. In which way the beam will bend depends on the way measurement is done: e.g. in the contact mode, tip is put in contact with the sample, which means that repulsive Coulomb's interaction dominates, and the end of cantilever bends upwards. Since the cantilever is short and stiff, Hooke's law can be applied. The deflection of the cantilevers end is given by  $x=F/k$ , where  $F$  is the force acting on the tip, ranging from nN to  $\mu\text{N}$ , and  $k$  is the effective spring constant of the probe.

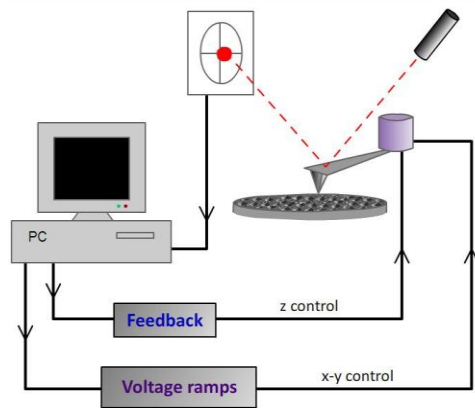


Figure 21. Schematic diagram of AFM probe with main parts

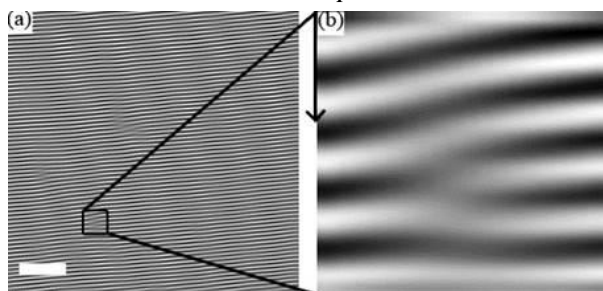


Figure 23: Edge dislocation in a copolymer thin film: white bar in a) is 200nm long, and the distance between white stripes in b) is 19nm. Credit: Andrew Marencic (Princeton University)

piezoelectrodes. Distortion of piezoelectric crystal under voltage bias is on the order of nanometer, as necessary for movement of AFM probe. By applying voltage bias on piezomotors, we can make AFM probe scan over the whole surface of the sample and collect deflection data. But as the probe scans over the sample, repeated bending of the cantilever will eventually cause wearing. To reduce it, deflection data is instead used for feedback control: when a change in deflection is detected, probe is moved in the z direction (up or down), thereby reducing the deflection. In this case height of the probe, proportional to voltage on the z-electrode, gives the data necessary to determine the sample topology. Movement of AFM probe with feedback control is shown on the Figure 22. In this way, deflection due to the atomic forces can be measured, and from that data, atomic forces can be measured. This in turn enables us to determine the surface topology of the given sample. AFM can be used to image the micro- and nano-scale morphology of a wide range of samples, including both conductive and insulating materials, and both soft and hard materials. For example, it can be used to image dislocations in metals and polymers, like collagen fibril (hair), and it can be even used to take pictures of live cells in a fluid environment. As with any instrument, there are a number of problems and artefacts that can arise during atomic force microscopy. Atomic force microscopy may be used to

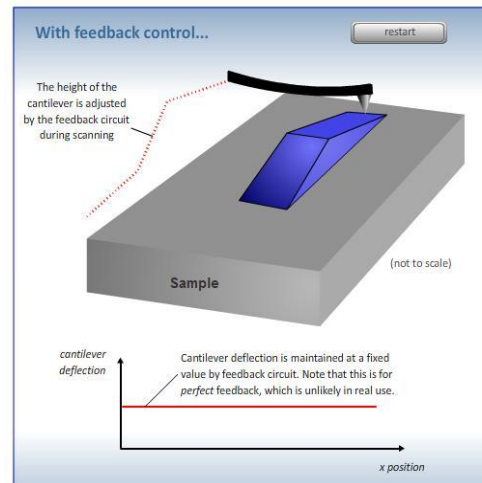


Figure 22. Movement of AFM probe with feedback control

Deflection of the cantilevers end is measured by reflecting a laser beam from the cantilever and detecting it with a sensitive photodetector, which consist of many photosensitive cells, enabling it to precisely detect where the laser beam hits it. Displacement of the cantilever will displace the reflected beam, and this displacement is detected by the photodetector. To scan the whole surface

of the sample, probe needs to be moved in x and y direction. Since this movement has to be precise on the order of nanometers, motors used for generating scanning motion are piezomotors, controlled by the voltage applied to

image the micro- and nano-scale morphology of a wide range of samples, including both conductive and insulating materials, and both soft and hard materials. Due to its high resolution and versatility, over the years AFM has had a significant impact in many disciplines, from materials science to biological and medical research. It also can be used for imaging dislocations in materials and for precise measurement of roughness. Besides that, because of its ability to image samples on an atomic scale, AFM had been and will continue to be vital to the advance of nanotechnology [16, 17].

## 5.2 Scanning Tunneling Microscopy – STM

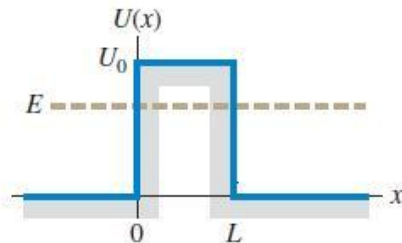


Figure 24. Energy barrier

Scanning tunneling microscopy also belongs to the family of scanning probe microscopy, and it shares many design features of AFM. Scanning tunneling microscope is actually a predecessor to AFM – it was invented in 1981. The functioning of STM is based on a purely quantum mechanical effect called tunneling. A particle of total energy  $E$  moves in  $+x$  direction, and on its way an energy barrier is placed /hill of height  $U_0$  between  $x=0$  and  $x=L$ . A simple model of barrier would consist of 2 identical metals with a thin insulator between them – an electron can easily move inside the metal, but cannot easily go through the insulator.

Classically, if  $E > U_0$ , the particle will always successfully go over the hill, slowing down while

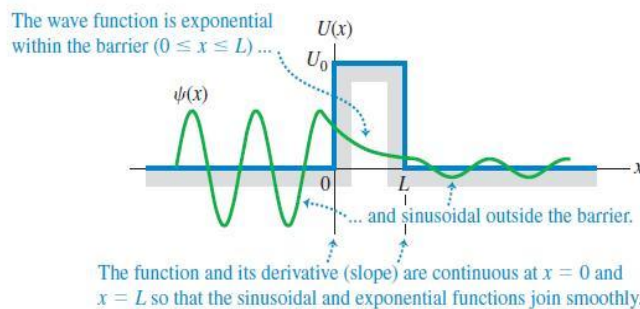


Figure 25. Sketch of wave function of tunneling particle

going over the hill: and if  $E < U_0$ , our particle will never be able to go over the hill, that is, it will be always reflected back. This is certainly true for macroscopic “particles” like a ball that is being thrown over the net. But for small particles like electrons, quantum-mechanical effects start to play a significant role. In quantum mechanics, matter has characteristics of both wave (frequency, wavelength) and of a particle (position, impulse)- this seemingly

contradictory idea, put forth by de Broglie. Another weird idea that proved to be correct was

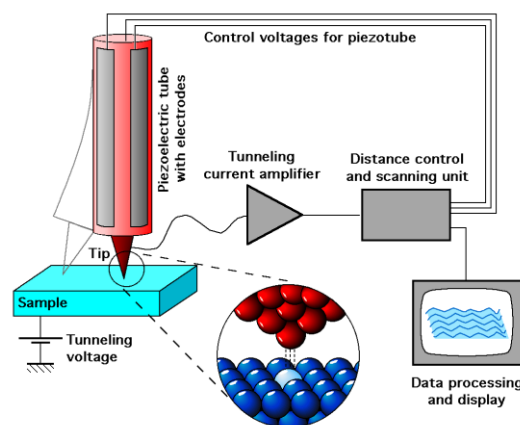


Figure 26. Schematic overview of STM

Heisenberg’s uncertainty principle. Since matter is described as both wave and particle, a balance is struck: if impulse/energy of matter is well known, then position/time interval is not, and vice versa. Wave-particle duality and Heisenberg’s uncertainty principle give rise to the phenomena of quantum tunneling. In contrary to the classical prediction, there is a finite probability that a particle with  $E < U_0$  will go over the energy hill and emerge on the other side of the hill. A simple way to represent the probability of tunneling is to sketch the wave function. In quantum mechanics, matter is mathematically described by a wave function - wave function alone has no clear physical meaning, but its square gives the probability density of finding the particle inside some interval. On the Figure 25. a

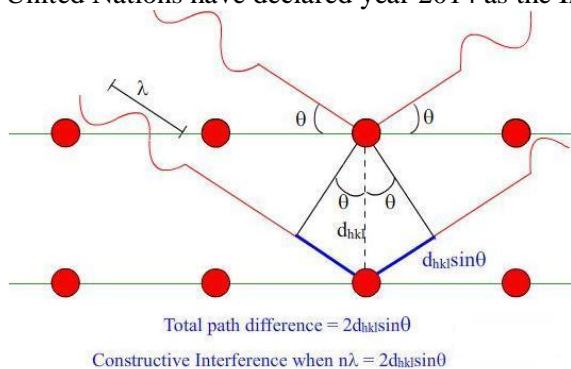
non-zero wave function behind the barrier means that there is a non-zero probability of finding a particle behind the barrier. Tunneling probability  $T$  strongly depends on the length of hill  $L$ , and height difference  $E - U_0$ . This strong dependence on length of barrier enables STM to obtain high resolution images, comparable to the size of a single atom. Scanning tunneling microscopes achieves such high resolution by using the basic apparatus shown in figure 26. An electrically conductive probe with a very sharp tip is brought near the surface of the sample, which also has to be conductive. Since both the tip and the sample are conductive, they are the two sides of the barrier, and the empty space between them represents the barrier we have been discussing. Because electrons obey quantum rules

rather than Newtonian rules, they can “tunnel” across the barrier of empty space, thereby producing a tunneling current. If there is no voltage between tip and sample, current is equal in both directions, resulting in zero net current - but if a voltage is applied between sample and tip, electrons in the atoms on the surface of the sample can tunnel preferentially from surface to tip to produce a tunneling current. In this way, the tip samples the distribution of electrons immediately above the surface. By monitoring the tunneling current as the tip is scanned over the sample, topography of the electron distribution on the surface can be obtained (a piece of graphite is very often used as a sample, like on Figure 26.). Since tunneling current depends strongly on the distance between surface and tip, STM has a very high resolution: 0.1 nm in lateral directions and 0.01nm depth resolution [20]. The STM has one serious limitation: Its operation depends on the electrical conductivity of the sample and the tip. Unfortunately, most materials are not electrically conductive at their surfaces. Even metals, which are usually excellent electrical conductors, are covered with nonconductive oxides.

### 5.3 X – ray crystallography

The X – ray crystallography is a 100 year old method which is still the most widely used method for determining atomic structure of crystalline materials, and which has helped determine the structure of many biological molecules like DNA, vitamins and proteins.

This method relies on using X-rays - electromagnetic radiation with wavelengths between roughly 0.01nm and 10nm, similar to the interatomic distances in a crystal. Since (visible) light diffracts when it encounters a structure of dimension similar to its wavelengths, German physicist Max von Laue expected to observe similar effect when a crystal is bombarded with X-rays. What he observed was diffraction, and this discovery earned him a Nobel Prize in Physics exactly 100 years ago. To commemorate this occasion and to emphasize the global importance of crystallography in human life, United Nations have declared year 2014 as the International Year of Crystallography



A simple model of diffraction on a surface of a crystalline material is shown on Figure 27. X-rays incident on two crystallographic planes are scattered by electrons of the atoms in the material – these rays are allowed to interfere in X-ray detector and depending on the angles, we will have constructive or destructive interference. By changing the incidence angle  $\theta$  and measuring the intensity of scattered beam, the data necessary to determine characteristics of sample is obtained.

Figure 27. Simple model of diffraction on crystal

In a more realistic model, there are more crystallographic planes, and diffraction occurs on each one of them. Also, orientation of crystallographic planes is not necessarily parallel to the surface of our sample, and there might be more than one crystal in our sample. Determining characteristics of given crystals is possible in this situation, but it is necessary to use more advanced physical models and mathematical tools to do so. X – ray crystallography has played a crucial role in characterizing many of the materials used today, and most notably, it helped determine the shape of DNA molecule, which enabled further development of genetics. [20]

### 5.4. Physical aspects of smartphone camera

Remote sensing is the collection of information relating to objects without being in physical contact with them. Thus our eyes and ears are remote sensors, and the same is true for cameras and microphones and for many instruments used in various applications. Remote sensing is the process of acquiring data/information about objects/substances not in direct contact with the sensor, by gathering its inputs using electromagnetic radiation or acoustical waves that emanate from the targets of interest. Remote sensing actually done from satellites as Landsat or airplane or on the ground. To repeat the essence of the definition above, remote sensing uses instruments that house sensors to view the spectral, spatial and radiometric relations of observable objects and materials at a distance. Most sensing modes are based on sampling of appropriate frequency photons in the electromagnetic (EM) spectrum. In much of remote sensing, the process involves an interaction between incident radiation and the targets of interest. Remote sensing also involves the sensing of emitted energy and the use of

non-emitted sensors. LIDAR or LADAR (Light Detection And Ranging) is an optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light, often using pulses from a laser. LIDAR technology has application in archaeology, geography, geology, geomorphology, seismology, forestry, remote sensing and atmospheric physics. An aerial photograph is a common example of a remotely sensed (by camera and film, or now digital) product [19].

We are witnesses of a tremendous growth of camera applications on smartphones these days. Every new generation of the camera modules offers higher resolution, better pictures in a smaller (or equal in size) package! We will discuss here some physical constrains of phone cameras. Camera of a smartphone is packed in a single module, which contains several lenses, voice coil motor which moves some of them to focus, sensor, and connectors. Entire package is ~5mm thick, and aperture of the front lens is about 1mm. Here is an example, LG module with 5 lenses.



The size of the module can't be increased because of the strict requirement of design - thin profile of a smartphone. At the same time, they offer more megapixels, which means that individual pixels on a sensor are becoming smaller. Nowadays, size of the pixels is so small (of order 1 μm) that it seems impossible to make them smaller and keep the same quality of the picture.

Another problem is the diffraction. If you have a lens with aperture of ~1mm, some diffraction effects are inevitable.

The intensity of the Fraunhofer diffraction pattern of a circular aperture is given by the squared modulus of the Fourier transform of the circular aperture:

$$I(\theta) = I_0 \left( \frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right)^2 = I_0 \left( \frac{2J_1(x)}{x} \right)^2 \quad \text{where } I_0 \text{ is the maximum intensity of the pattern at the}$$

airy disc center,  $J_1$  is the Bessel function of the first kind of order one,  $k = 2\pi/\lambda$  is the wave number,  $a$  is the radius of the aperture, and  $\theta$  is the angle of observation, i.e. the angle between the axis of the circular aperture and line between aperture center and observation point.  $x = k a \sin \theta = \frac{2\pi a}{\lambda} \frac{q}{R} = \frac{\pi q}{\lambda N}$ ,

where  $q$  is the radial distance from the optics axis in the observation (or focal) plane and  $N = R/d$  ( $d = 2a$  is the aperture diameter,  $R$  is the observation distance) is the  $f$ -number of the system. If a lens after the aperture is used, the airy pattern forms at the focal plane of the lens, where  $R = f$  ( $f$  is the focal length of the lens). Note that the limit for  $\theta \rightarrow 0$  (or for  $x \rightarrow 0$ ) is  $I(0) = I_0$ . The zeros of  $J_1(x)$  are at  $x = k a \sin \theta \approx 0, 3.8317, 7.0156, 10.1735, 13.3237, 16.4706 \dots$ . From this follows that the first dark ring in the diffraction pattern occurs where  $k a \sin \theta = 3.8317 \dots$ , or

$$\sin \theta \approx \frac{3.83}{ka} = \frac{3.83\lambda}{2\pi a} = 1.22 \frac{\lambda}{2a} = 1.22 \frac{\lambda}{d}$$

to the  $f$ -number by  $q_1 = R \sin \theta \approx 1.22 \frac{R\lambda}{d} = 1.22 \lambda N$ , where  $R$  is the distance from the aperture, and the

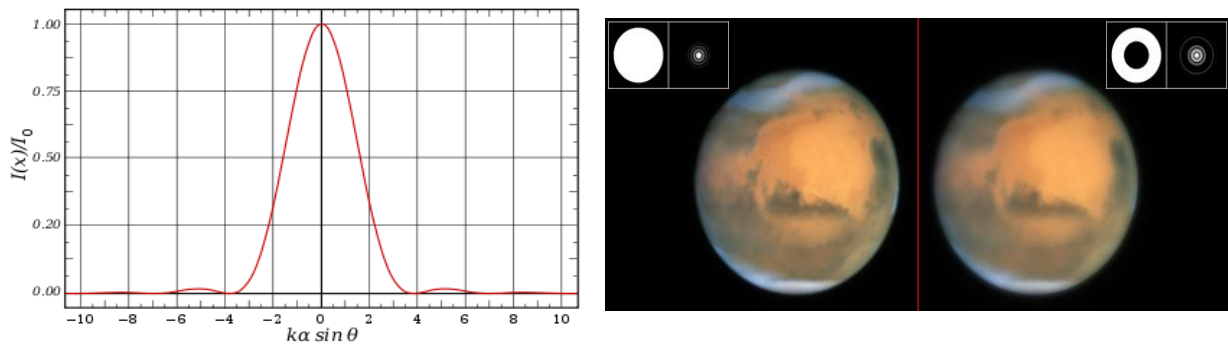
$f$ -number  $N = R/d$  is the ratio of observation distance to aperture size. The half maximum of the central Airy disk (where  $J_1(x) = x/2\sqrt{2}$ ) occurs at  $x = 1.61633 \dots$ ; the  $1/e^2$  point (where  $J_1(x) = x/2e$ ) occurs at  $x = 2.58383 \dots$ , and the maximum of the first ring occurs at  $x = 5.13562 \dots$

The intensity  $I_0$  at the center of the diffraction pattern is related to the total power  $P_0$  incident on the aperture  $I_0 = \frac{E_A^2 A^2}{2R^2} = \frac{P_0 A}{\lambda^2 R^2}$ , where  $E$  is the source strength per unit area at the aperture,  $A$  is the area

of the aperture and  $R$  is the distance from the aperture. At the focal plane of a lens,  $I_0 = \frac{P_0 A}{\lambda^2 f^2}$ . The

intensity at the maximum of the first ring is about 1.75% of the intensity at the center of the airy disk. The expression for  $I(\theta)$  above can be integrated to give the total power contained in the diffraction pattern within a circle of given size:  $P(\theta) = P_0 [1 - J_0^2(ka \sin \theta) - J_1^2(ka \sin \theta)]$ , where  $J_0$  and  $J_1$  are

Bessel functions. Hence the fractions of the total power contained within the first, second, and third dark rings [18, 19]. Here down is graph of intensity of pattern and an example on real picture.



## 6. CONCLUSION

The main and selected physical processes that enable the functioning of many modern measuring/technical instruments, which are widely used in scientific research and measurement techniques are described and simple explained. These are different types of sensors, various interferometers and spectrometers (Laser Doppler anemometers (LDA, PDA, CTA)), atomic force microscope (AFM), scanning tunneling microscope (STM) and X-ray crystallograph.

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