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MEASURE THE IMPACT OF WIRELESS TECHNOLOGIES ON TEM

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NÁZEV TÉMATU:

Měření vlivu bezdrátových technologií na TEM

POKYNY PRO VYPRACOVÁNÍ:

Seznamte se s dostupnými bezdrátovými technologiemi pro přenos dat a porovnejte jejich parametry. Nastudujte teorii transmisních elektronových mikroskopů (TEM). Odvoďte z teorie moduly nebo místa v mikroskopu, která jsou nejcitlivější na RF rušení. Navrhněte, proměřte a vyhodnoťte vliv vybraných technologií na parametry TEM.

DOPORUČENÁ LITERATURA:

Podle pokynů vedoucí práce.

Termín zadání: 5. 2. 2018 ***Termín odevzdání:*** 22. 5. 2018

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Abstract

The purpose of this diploma thesis is to research and compare available wireless communication technologies (frequency, modulation type, transmission speed and consumption). Describe transmission electron microscopes theory and deduce the most sensitive microscope parts to high frequency distortion. Investigate effect of wireless technology on CE standards and come up with, perform and evaluate the influence measurement of chosen technologies on base parameters of transmission electron microscope.

Abstrakt

Úkolem diplomové práce je prozkoumat dostupné bezdrátové technologie (pro přenos dat) porovnat jejich parametry (nosná frekvence, typ modulace a kódování, rychlost přenosu, spotřeba/výkon, …), popsat teorii transmisních EM, odvodit z teorie moduly nebo místa TEMu nejvíce citlivá na RF rušení a prozkoumat vliv bezdrátových technologií na aplikovatelné normy (pro udělení CE) a dále navrhnout, provést a vyhodnotit měření vlivu vybraných technologií na hlavní parametry TEMu.

Key words

TEM, microscope, transmission, distortion, EMC

Klíčová slova

TEM, mikroskop, transmisní, rušení, EMC

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Declaration

I hereby declare that I have elaborated my master´s thesis on the theme of "Measure the impact of wireless technologies on TEM" independently, under the supervision of the diploma thesis supervisor and with the use of technical literature and other sources of information which are all quoted in the master´s thesis and detailed in the list of literature at the end of the master´s thesis. As the author of the master´s thesis I furthermore declare that, concerning the creation of this master´s thesis, I have not infringed any copyright. In particular, I have not unlawfully encroached on anyone´s personal copyright and I am fully aware of the consequences in the case of breaking Regulation § 11 and the following of the Copyright Act No 121/200 Vol., including the possible consequences of criminal law resulted from Regulation § 152 of Criminal Act No 140/1961 Vol.

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Brno 15.5.2018 ....

(author´s signature)

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List of symbols, physical constants and abbreviations

BF	Bright-field
CMOS	Complementary Metal-Oxide-Semiconductor
DF	Dark-field
EELS	Electron energy loss spectrometer
FEG	Field Emission Gun
HAADF	High-angle annual dark field
LaB_6	Lanthanum hexaboride
STEM	Scanning Transmission Electron Microscope
TEM	Transmission Electron Microscope
FEG	Field Emission Gun
SEM	Scanning Electron Microscope

1. Introduction

Wireless technology is experiencing a huge boom today. The trend is to remove the use interfering cables where it is technologically possible. This is basically wherever it is not necessary transfer power supply. Wireless technologies are used for data transfer, creating local computer networks and Internet sharing, or for audio or video transmission. The aim of this thesis is to compare and analyse possibility to replace wire connection in transmission microscopes.

The invention of the optical microscope, over 400 years ago enables us to look closely to different things. It is not invention of one person but with the beginning of microscopy are connected names like Zacharias and John Jansen, Galileo Galilei, Johan Kepler, Antonius van Leuwenhoek or Robert Hooke. This invention was really important development and it opened the door to new science area. From that time, it has been improving to the high-resolution microscopes which we have nowadays. During the improvement of the microscopes, scientists came to a crucial obstacle and so that by the usage of light is not possible to observe objects smaller than wavelength of used light. This problem was solved by usage of electron beam. First TEM was built on Germany in 1930s, and with some changes is used by nowadays.

Electromagnetic compatibility is a field of reliability individual electrical and electronic equipment. It examines the links between individual elements or systems that must be defined in such systems did not interfere with each other negatively. This branch also examines the interference the device creates and at the same time interferes with the device. The result should be that the different devices do not adversely affect each other while being resilient against interference from the external environment.

2. Wireless communication

Wireless communication, or sometimes simply wireless, is the transfer of information or power between two or more points that are not connected by an electrical conductor. The most common wireless technologies use radio waves. With radio waves distances can be short, such as a few meters for Bluetooth or as far as millions of kilometres for deep-space radio communications.

2.1. Wi-Fi

Wi-Fi is a technology for wireless local area networking with devices based on the IEEE 802.11 standards. Wi-Fi most commonly uses the 2.4 GHz and 5.8 GHz radio bands.

Figure 1: Symbol of wi-fi [1]

Wi-Fi connections can be disrupted or the Internet speed lowered by having other devices in the same area. Many 2.4 GHz 802.11b and 802.11g access-points default to the same channel on initial start-up, contributing to congestion on certain channels. Wi-Fi pollution, or an excessive number of access points in the area, especially on the neighbouring channel, can prevent access and interfere with other devices' use of other access points, caused by overlapping channels in the 802.11g/b spectrum, as well as with decreased signal-to-noise ratio (SNR) between access points. This can become a problem in high-density areas, such as large apartment complexes or office buildings with many Wi-Fi access points.

The Wi-Fi is divided into 11 channels in US, 13 channels in Europe and 14 in Japan. It is important to prevent interference between other devices using 802.11g/b standard. A Wi-Fi signal occupies five channels in the 2.4 GHz band. Any two channel numbers that differ by five or more, such as 2 and 7, do not overlap. The oft-repeated adage that channels 1, 6, and 11 are the only non-overlapping channels is, therefore, not accurate. Channels 1, 6, and 11 are the only group of three non-overlapping channels in North America and the United Kingdom. In Europe and Japan using Channels 1, 5, 9, and 13 for 802.11g and 802.11n is recommended.

Other devices use the 2.4 GHz band:

- microwave ovens,
- ISM band devices,
- security cameras,
- ZigBee devices,
- Bluetooth devices,
- video senders,
- cordless phones,

and, in some countries, amateur radio, all of which can cause significant additional interference. It is also an issue when municipalities or other large entities (such as universities) seek to provide large area coverage

The Wi-Fi signal range depends on the frequency band, radio power output, antenna gain and antenna type as well as the modulation technique. Line-of-sight is the thumbnail guide but reflection and refraction can have a significant impact.

2.2. Bluetooth

Bluetooth technology was made by Jaap Haartsen and Sven Mattison from Eriksson company on 1994.

Figure 2:Symbol of Bluetooth [2]

Bluetooth is wireless communication technology which is used for connecting two or more devices. Between these devices is PAN (created personal area network). Bluetooth is working in ISM radio bands with frequencies about 2,4Ghz (2,400 – 2,4835 Ghz), 72 radio channels with 1MHz distance. To suppress interference with other signals running on ISM, uses the Bluetooth method of frequency jumps (frequency hopping). [2]

Bluetooth v3.0/v4.0

- Theoretical speed: - 24Mb/s (with use of wi-fi),
  - without 3Mb/s
- Power input: - class 1 (100mW, 20 dBm, 100m)
  - class 2 (2,5mV, 4dBm, 10m)
  - class 3 (1mW, 0dBm, 1m)

2.3. ZigBee

Zigbee is a low-cost, low-power, wireless mesh network standard targeted at battery-powered devices in wireless control and monitoring applications. Zigbee operates in the industrial, scientific and medical (ISM) radio bands: 2.4 GHz in most jurisdictions worldwide; though some devices also use 784 MHz in China, 868 MHz in Europe and 915 MHz in the USA and Australia. Data rates vary from 20 kbit/s (868 MHz band) to 250 kbit/s (2.4 GHz band).

Figure 3:Symbol of ZigBee [3]

The Zigbee network layer natively supports both star and tree networks. Every network must have one coordinator device

2.4. NFC

Near-field communication (NFC) is a set of communication protocols that enable two electronic devices to establish communication by bringing them within 4 cm of each other.

NFC devices are used in contactless payment systems, similar to those used in credit cards and electronic ticket smartcards and allow mobile payment to replace/supplement these systems.

Figure 4:Symbol of NFC [4]

NFC employs electromagnetic induction between two loop antennas when NFC-enabled devices—for example a smartphone and a printer—exchange information, operating within the globally available unlicensed radio frequency ISM band of 13.56 MHz on ISO/IEC 18000-3 air interface at rates ranging from 106 to 424 kbit/s. [4]

Each full NFC device can work in three modes:

- NFC card emulation—enables NFC-enabled devices such as smartphones to act like smart cards, allowing users to perform transactions such as payment or ticketing.
- NFC reader/writer—enables NFC-enabled devices to read information stored on inexpensive NFC tags embedded in labels or smart posters.
- NFC peer-to-peer—enables two NFC-enabled devices to communicate with each other to exchange information in an ad hoc fashion.

2.5. Wireless USB

Wireless USB is a short-range, high-bandwidth wireless radio communication protocol. WUSB is designed to replace conventional USB. WUSB is not designed to create computer networks (even if it is theoretically possible). The parameters are similar to conventional USB 2.0 but speed is highly dependable on distance. For example, within 3m is about 480mbit/s but when reaches 10m than decreased on 110 mBit/s (optimal conditions)

Figure 5: wireless USB [5]

WUSB offers the same communication model as standard USB. One point works as a master (host, server, control device), the other as a client. The Master always controls the entire communication and the client only responds to requests. The WUSB architecture allows direct connection to the master for up to 127 devices.

Recently WUSB introduced a new Device Wire Adapter (DWA), sometimes referred to as the "WUSB hub". DWA allows you to connect an existing USB 2.0 device to a wireless WUSB using the WUSB client. [5]

2.6. FWA

Fixed Wireless Access (FWA), also called Wireless Local Loop, is a wireless network providing Point-to-Multipoint broadband connectivity. The meaning of the word fixed in the name indicates and assumes that the end user's connection is fixed (permanent).

Figure 6: Symbol of FWA [6]

According to the transmission band, the FWA networks are divided into two groups:

- The first option uses a narrower bandwidth in GHz (1.8, 2.4, or 3.5 GHz) to provide transmission speeds up to hundreds of kilobits per second.
- The second variant broadcasts at higher frequencies of a wider band of GHz (10.5, 26, 28 or 40 GHz). For broadcasts in higher bands, the baud rate is up to 30 Mb/s

3. EMC -Electromagnetic compatibility

Electromagnetic compatibility (EMC) is the branch of electrical engineering concerned with the unintentional generation, propagation and reception of electromagnetic energy which may cause unwanted effects such as electromagnetic interference (EMI) or even physical damage in operational equipment. The goal of EMC is the correct operation of different equipment in a common electromagnetic environment [29]

3.1. EMC of biological systems

EMC of biological systems is aiming to electromagnetic background and their effects on living creatures. Effects of EMC on biological systems depend primarily on the time of exposure to the electromagnetic field, its character and also on the characteristics of the living organism itself.

3.2. EMC of technical systems

Electromagnetic compatibility can be analysed from two basic factors. The first factor is to investigate the noise emission, and the second is to determine the resistance of the device against interference.

It must be taken into account the analysis of undesirable effects observed within EMC assumes that any device (electrical device) or system, or its arbitrary the part may be also a source of interference and the interference receiver (influenced object). Therefore, we can investigate EMC from the EMC core chain

3.2.1. Electromagnetic interference

Disturbing electromagnetic energy is most commonly propagated by galvanic bonding, in a telecommunication line or in a low voltage power line. This energy then affects the correct operation of other electrical devices.

Another way that parasitic electromagnetic energy can spread is radiation to the surrounding area. In that case, we are talking about disturbing electromagnetic field.

3.2.2. Sources of interference

Any electro technical systems can be considered as a source and as a receiver of electromagnetic interference. But there is a certain group of systems where the process of generating interference is greater than their unwanted income. This group is called sources of interference.

These sources of interference include, above all, television and radio transmitters or even clock signals of electronic circuits. Signals from these sources are either parasitically injected into cable or spread by radiation. We may include broadcasting of non-public radio communication systems as sources of interference. (mentioned in chapter 2.0.)

4. Transmission Electron microscopy

The transmission electron microscope was invented by Max Knoll and Ernst Ruska in Berlin during the 1931 – 1934. The TEM has magnification and resolution capabilities which are over a thousand times beyond those offered by the light microscope. The light is replaced by the electron beam emitted in the vacuum and the glass lenses are replaced by the electromagnetic lenses. [32]

Electrons are emitted in the electron gun by thermionic, Schottky, or field emission. The latter are used when high gun brightness and coherence are needed. A three- or four-stage condenser-lens system permits variation of the illumination aperture and the area of the specimen illuminated. The electron- intensity distribution behind the specimen is imaged with a lens system, com- posed of three to eight lenses, onto a fluorescent screen. The image can be recorded by direct exposure of a photographic emulsion or an image plate in- side the vacuum, or digitally via a fluorescent screen coupled by a fibre-optic plate to a CCD camera.

Electrons interact strongly with atoms by elastic and inelastic scattering. The specimen must therefore be very thin, typically of the order of 5–100 nm for 100 keV electrons, depending on the density and elemental composition of the object and the resolution desired.

4.1. Physics of electron

The particle moving through magnetic field is affected by Lorentz force, which equals:

$$\vec{F} = q(\vec{v} * \vec{B}) \tag{1}$$

q… charge of particle
v… vector of speed
B… vector of magnetic induction

The result of the vector product is a vector that is perpendicular to the two input vectors and forms a right-handed coordinate system with them.

The magnitude of the result is given by the lengths of the input vectors and the angle they conceal. The size of Lorentz's power of equality equals:

$$|\vec{F}| = |q| * v * B * \sin(\alpha) \tag{2}$$

α … angle between vectors v and B

size of vector can´t be negative so only absolute value is used in case of q

4.2. Principle of coils

There are used direct current coils in Fei microscopes. Electromagnetic lenses are only positive (converting).

There are multipole lenses usually quadrupole, Multipole Lenses. A quadrupole lens can be constructed from four pole-pieces of opposite polarity. Because the magnetic field is normal to the electron beam, a stronger Lorentz force is exerted. A point object is focused as a line image, as with a cylindrical lens in light optics. In electron microscopes, quadrupole lenses are used as stigmators for compensating the axial astigmatism or to correct the focusing distance of an electron prism for energy analysis.

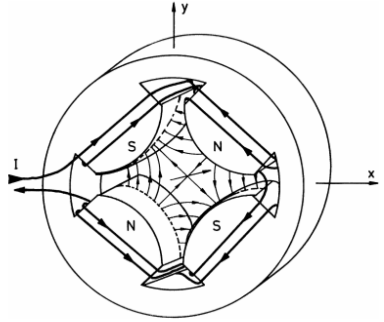

Figure 7: Quadrupole lenses [15]

Magnetic lenses with short focal lengths are obtained by concentrating the magnetic field by means of magnetic polepieces. Figure 8 shows the distribution of a magnetic field produced by a coil enclosed in an iron shield, apart from an open slit. [15]

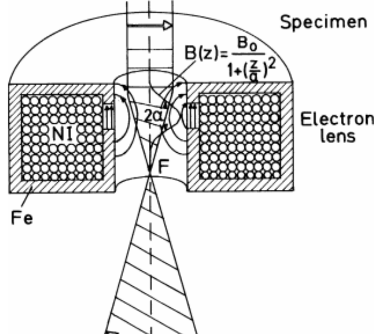

Figure 8: distribution of a magnetic field [15]

The magnetic field has rotational symmetry. Due to effect of coils the electron beam rotates. Because of that it´s nearly impossible to change magnification continuously. Instead of that we change magnification on steps which are calculated to not rotate image.

4.3. Lens aberrations

There are five possible isotropic aberrations of third order in lenses with rotational symmetry, as in light optics:

1. spherical aberration
2. astigmatism
3. field curvature
4. distortion
5. coma

There are three further anisotropic aberrations:

1. anisotropic coma
2. anisotropic astigmatism
3. anisotropic distortion

4.3.1. Spherical Aberration

The spherical aberration has the effect of reducing the focal length for electron rays passing through outer zones of the lens Electrons crossing the optic axis at different angles θ or scattered in the specimen through angles θ will intersect the Gaussian image plane at a distance from the paraxial image point. [15]

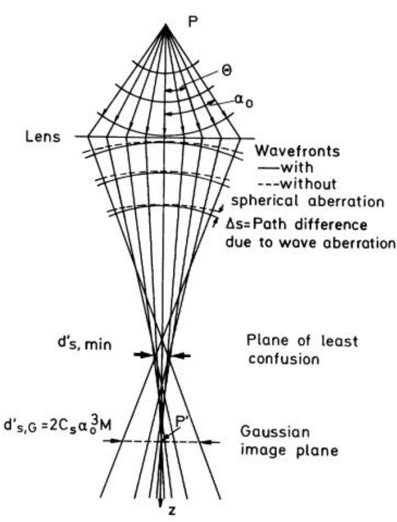

Figure 9: Spherical Aberration [15]

- Cs is the spherical-aberration coefficient
- M the magnification.

4.3.2. Astigmatism and Field Curvature

Astigmatism is similar to coma but arises for small objects at the edges of the field striking an uncorrected lens asymmetrically. It is not as sensitive to aperture as coma. The incoming rays passing through the lens in oblique angel with respect to the optical axis focus differently from those paraxial. Depending on the incidence angle of the off-axis rays entering the lens, the refracted plan is oriented either tagentially or sagittally. So, the resulting image depends upon the location of the focal plan and thus produces blurry image more or less elongated which intensity and contrast decrease as the distance from the centre increases. [15]

Field Curvature, also known as "curvature of field" or "Petzval field curvature", is a common optical problem that causes a flat object to appear sharp only in a certain part(s) of the frame, instead of being uniformly sharp across the frame. This happens due to the curved nature of optical elements, which project the image in a curved manner, rather than flat. And since all digital camera sensors are flat, they cannot capture the entire image in perfect focus. [33]

4.3.3. Distortion

Distortion causes a displacement in the Gaussian image plane for off-axis points. This results in a geometrical distortion of a square, which is known as pin cushion distortion. The spherical aberration may be used to explain an image distortion found in intermediate and projector lenses operating at low magnifications. These large-bore lenses magnify an intermediate image in which the angular aperture at any image point is smaller by a factor 1/M than the objective aperture αo. Therefore, no further decrease of image resolution by the spherical aberration is expected. However, a distortion of the image can be generated indirectly by the spherical aberration. This compensation of distortion is very important for preliminary exploration of the specimen at low magnification. [15]

4.3.4. Coma

Coma causes a cone of rays passing through the specimen point P at an off-axis distance r at angles θ to the axis to be imaged as a circle with radius proportional to θ2 and r. The centre of the circle does not coincide with the Gaussian image point but is shifted in the radial direction by twice the radius. Coma-free alignment is necessary for high resolution. [15]

4.3.5. Anisotropic Aberrations

The anisotropic distortion is caused by the dependence of the image rotation on the off-axis distance r of the object point; the latter is imaged with an additional rotation angle φ proportional to r^2. Straight lines in the specimen plane become cubic parabolas in the image plane. Reversal of the lens current changes the sense of rotation. [15]

4.4. TE Microscope

The Transmission electron microscope is made up of different basic systems which together form one functional unit capable of orienting and imaging extremely thin specimens. System is divided into four groups: the **illuminating system**, the **specimen manipulation system**, the **imaging system** and the **vacuum system**.

4.4.1. Vacuum system

Vacuum system is set of pumps, switches and valves used for evacuating air from the microscope. The vacuum prevents high voltage discharges and obtain free path for electron beam. Vacuum system is divided into three parts dependable on required level of vacuum. There are usually used 3 types of pumps.

- PVP (rotary pump)
- TMP (turbo molecular pump)
- IGP (ion pump)

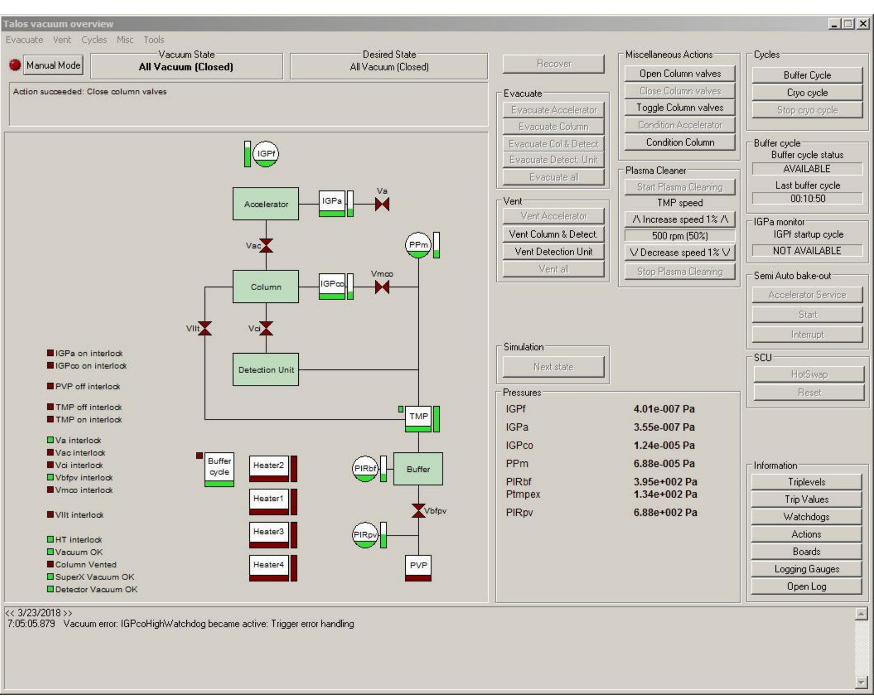

Figure 10: Vacuum scheme of Talos microscope

In the vacuum system various pumping vacuum cycles can be distinguished. These cycles always serve a particular purpose such as:

Pre-pumping cycle:

At start up, the pre-vacuum pump evacuates the lines, the buffer and all other chambers to a vacuum of 19 Pa. After that the vacuum system waits until the TMP has reached its working speed. Once the signal of full speed is present, the pre-vacuum pump evacuates once again the lines, the buffer and all other chambers. After that the High vacuum cycle starts.

High vacuum cycle:

As already said, this cycle starts once the TMP has reached its working speed and all chambers are at 0.013 Pa. Ultra-high vacuum cycle starts.

Ultra-high vacuum cycle:

Now the Ion getter pump is started and pumps together with the TMP on the projection chamber, and column chambers. This is done either for one minute or until the vacuum reaches a value of 0.0013 Pa. Once the vacuum system has reached the UHV cycle the column is separated from the projection chamber, so that the IGP is pumping alone. The High tension can now be switched on. The column is effectively separated from the projection chamber, a differential pumping aperture of 300μm is present. Several other cycles are made to ensure that parts can be introduced in the microscope.

Specimen airlock cycle:

The specimen can be exchanged without introducing air. This is done automatically when introducing a new specimen. This causes the pre-vacuum pump to start, evacuates the lines and the buffer, opens the airlock valve and pumps the specimen airlock chamber.

PVP

Rotary pump is used for evacuating the airlock. For the pre-vacuum or evacuating buffer. PVP is able to reduce pressure to 10^{-1} Pa. Rotary pump crates vibrations that cause distortions. Before every measurement is recommended to shut down rotary pump.

In a rotary pump a rotor is mounted eccentrically in a cylindrical housing. Two sliding valves are mounted in channel in the rotor. Theses valves push against the rotor wall via a spring and the centrifugal forces.

During each turn a little bit of oil is sucked into the pump to grease the valves and get a better sealing. The attainable final vacuum is about 1,3 Pa, depending on the amount of air that is dissolved in the oil and the amount of air that is leaking from the pressure to the suction side. This implies that if a pump has two rotors in series a lower final pressure can be obtained (about 0,13 Pa). This type of rotary pump is generally used to rough the vacuum to a so-called pre-vacuum. [7]

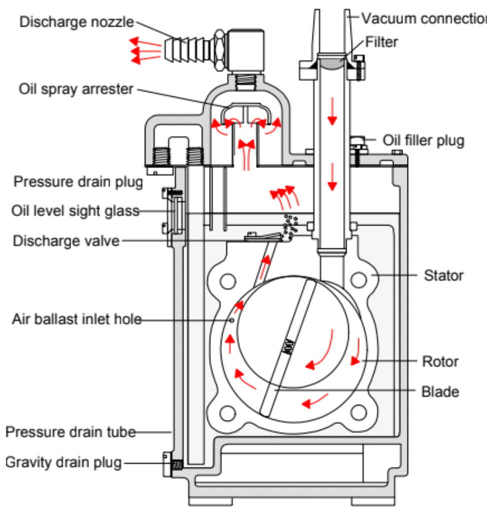

Figure 11: Scheme of PVP [7]

TMP

Turbo molecular pump is main part of the vacuum and is able to reach pressure about 10^{-8} Pa ad is used for evacuating the IDU and column. It has several advantages such as low vibration or ability to deal with humidity in the microscope. Distortion of TMP depends on quality of manufacturing. TMP may cause distortion dependable on the rotation speed which can cause problems in HT-STEM. TMP is usually cooled by water and can run without cooling about two hours

A gas molecule that is touched by a fast-moving angled wall of a rotor blade receives from this blade an extra speed component V in the direction of the pre-vacuum side of the pump. The cause can be twofold:

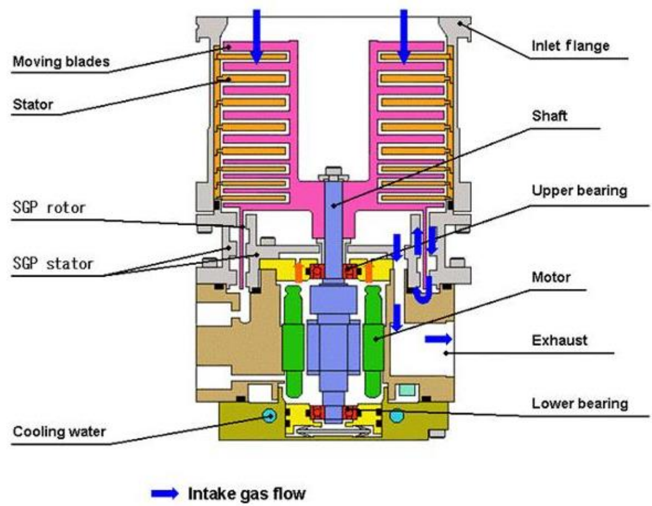

Figure 12: Scheme of TMP [34]

- A complete elastic collision with the wall so that the molecule gets an extra impulse.
- The gas molecule is attached to the wall by means of adhesion forces and is released by kinetic energy force. [7]

Because of the speed of the blade, the collision is much more probable from one side of the angled blade than from the other. When releasing the molecules, they have acquired a direction and so there is pumping speed. The gas molecules collide alternatively with angled walls of both the rotors and the stators. Because of the kinetic energy the molecules also move back against the pumping direction (back diffusion). When the back diffusion equals the pumping speed the pump has reached its final pressure. [7]

IGP

Ion pump is used for evacuating the column and electron gun where is requirement of high vacuum. One of the disadvantages of ion pup is that disability to handle humidly and lifetime dependable on quality of vacuum and contamination. IGP is also used for measure of vacuum, because pressure is comparable of electric current flowing through IGP.

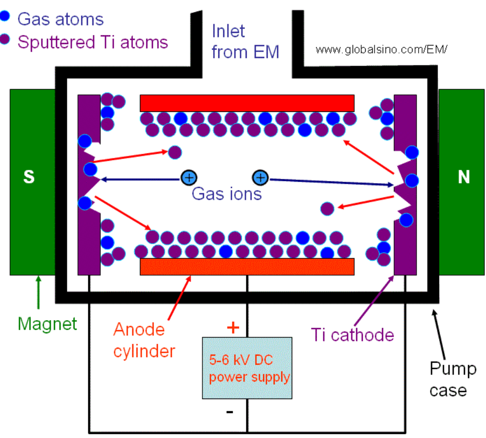

Figure 13: Scheme of IGP [35]

An ion pump (also referred to as a sputter ion pump) is a type of vacuum pump capable of reaching pressures as low as 10^{-11} mbar under ideal conditions. An ion pump ionizes gas within the vessel it is attached to and employs a strong electrical potential, typically 3–7 kV, which allows the ions to accelerate into and be captured by a solid electrode and its residue

4.4.2. Illumination system

The system is situated on the very top of the microscope. It consists of the **electron gun** and **condenser lenses**. This part of microscope is responsible for creating and aligning beam before it reaches objective lenses and specimen.

Main function of **electron gun** is to provide beam of electrons. Specification of beam has main influence on quality of image. Electron gun comprises a cathode (filament). Different types of electron filaments are used. There are two bas groups of sources, thermo emission and auto emission.

- Tungsten wire
- Lanthanum hexaboride (LaB_6)
- Schottky filed emitter (SFE)
- Cold field emission gun (FEG)

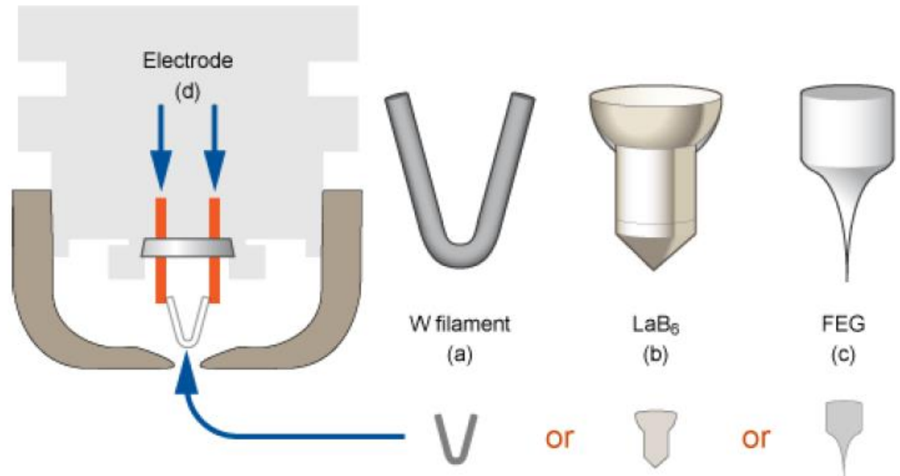

Figure 14: Types of filaments [8]

The most widely used thermionic cathodes consist of a tungsten wire 0.1–0.2 mm in diameter bent like a hairpin and soldered on contacts. The wire is directly heated by a current of a few amperes.

Increasing the cathode temperature leads to a broadening of the Fermi distribution f(E) at the Fermi level E_F, and for high temperatures, electrons in the tail of the Fermi distribution acquire enough kinetic energy to overcome the work function φ_w. The current density j_c (A m^{-2}) of the cathode emission can be estimated from Richardson's law,

$$j_c = AT_C^2 \exp(-\varphi_w/kT_c), \qquad (3)$$

where $k = 1.38 \times 10^{-23}$ J K^{-1} is Boltzmann's constant, T_c is the cathode temperature, and A= 12×105 A K^{-2} m^{-2} is a constant that depends on the cathode material. Most metals melt before they reach a sufficiently high temperature for thermionic emission. An exception is tungsten, which is widely used at a working temperature Tc of 2500–3000 K (melting point Tm = 3650 K).

Lanthanum hexaboride (LaB6) cathodes consist of small, pointed crystals They require indirect heating because their electrical resistance is too high for direct-current heating. The heating power can be decreased by supporting a small crystal between carbon rods or fibers or binding it to refractory metals (rhenium or tantalum) that have a low rate of reaction with LaB6. These cathodes need a better vacuum than tungsten cathodes to reduce the damage caused by positive-ion bombardment. With Tc = 1400–2000 K are also employed because their work function is lower. The tungsten metal evaporates continuously during operation, limiting the lifetime of the filament, which decreases from 200 h to 5 h if Tc increases from 2500K to 2900K [15]

So-called **Schottky emission** cathodes are of the ZrO/W(100) type with a tip radius r 0.1–1 μm. Just after etching, the middle of the rod is coated with ZrH2 powder, which dissociates at 1800K in UHV and lets metallic Zr diffuse to the tip. Zirconium oxide is formed at 1600 K for a few hours at a partial oxygen pressure of 10^{-4}–10^{-5} Pa and flashed for a few seconds at 2000 K. The field strength at the cathode is much higher than in thermionic cathodes but is still ten times lower than in field-emission sources. When using a **Schottky cathode,** In contrast to field emission, discussed below, the electrons still have to overcome work function $\varphi_{w,eff}$ by their kinetic energy, which is furnished by heating the cathode. [15] In FEI transmission microscopes is Schottky FEG used with tip radius: 0.5 micron and operating temperature 1800K.

Figure 15: FEI gun [36]

Tungsten is normally used as the tip material because etching is easy, but it has the disadvantage of sensitivity to surface layers. Wires of 0.1 mm diameter are spot-welded on a tungsten hairpin cathode and electrolytically etched to a radius of curvature of about 0.1 μm. In **Field Emission** the width b of the potential barrier at the metal–vacuum boundary decreases with increasing E; for $|E| \geq 109$ V m^{-1}, using a tip radius $r \leq 0.1$ μm, the width b becomes less than 10 nm and electrons at the Fermi level can penetrate the potential barrier by the quantum-mechanical tunnelling effect. The emitted electrons do not need to overcome the potential barrier and it is not necessary to heat the cathode, whereas this is essential for thermionic and Schottky emissions. If a field-emission source is heated, it is mainly to prevent the adsorption of gas molecules. [15]

Table 1: Tip parameters

	Tungsten hairpin	**Pointed LaB_6 rod**
T_C	2500-3000 K	1400–2000 K
Φ_w	4.5 eV	2.7 eV
j_C	$(1-3) \times 10^4$ A/m^2	$(2-5) \times 10^5$ A/m^2
β	$(1-5) \times 10^9$ A/m^2 sr	$(1-5) \times 10^{10}$ A/m^2 sr
ΔE	1.5–3 eV	1–2 eV
d	20–50 μm	10–20 μm
p	$\leq 10^{-3}$ Pa	10−4 Pa
|E|	10^6 V/m	

Table 2: Tip parameters

	Schottky emission	**Field emission**
T_C	1800 K	Tc = 300 K
Φ_w	2.7 eV	4.5 eV
j_C	5×10^6 A/m^2	109 − 1010 A/m2
β		$2 \times 10^{12} - 2 \times 10^{13}$ A/m^2 sr
ΔE	0.3–0.7 eV	0.2–0.7 eV
r	0.5–1 μm	≤ 0.1 μm
d	15 nm	2.5 nm
p	≤ 10−6 Pa	≤ 10−8 Pa
|E|	2×10^8 V/m	5×10^9 V/m

Characteristic parameters:

- Cathode temperature T_c
- Tip radius r of pointed cathodes
- Work function φ_w
- Diameter d of source
- Emission current density j_c
- Operating vacuum p
- Gun brightness β at E = 100 keV
- Field strength |E| at cathode
- Energy spread ΔE

The base parameter is directional current density B (brightness) determines current of electrons I which is emitted from the surface S with angle Ω where α_0 is emitting angle and d_z is diameter of filament.

$$B = \frac{I}{S\Omega} \approx \frac{4I}{\pi^2 \alpha_0^2 d_z^2} \quad (4)$$

The **condenser** lenses are the last and very important part of illuminating system. It gathers the electrons of the first crossover image from the gun and focuses electrons onto the specimen. Modern TEMs have two condenser lenses. The first one magnifies the electron beam so that the gun crossover is reduced to the spot size of size in a range 20 µm –1 µm. For change, the second condenser lens enlarges the spot size. The aim of these two condenser lenses is to precisely control the amount of electron irradiation so that just the area being examined is illuminated. Accordingly, at the higher magnifications smaller spot sizes should be focused on the specimen and at lower magnifications larger spot sizes can be used. Thanks to the spot size control, the beam damage of the specimen is possible to minimize. [8]

An aperture is also a part of the condenser lens. Depends on the construction of the microscope, both condenser lenses can have apertures of variable sizes. Usually, the first one has fixed aperture size but the second lens allows insert to the path of electron beam apertures of different sizes. The larger condenser aperture, the more electrons passing through, the brighter spot on the specimen obtained. Smaller apertures reduce the illumination on the specimen. It is important to remember that larger condenser aperture gives more illumination to the specimen but there is bigger spherical aberration. [8]

4.4.3. Specimen manipulation system

It provides computer-controlled movement of the specimen holder across five axes. The translation movements are: X, Y and Z and the rotation movements are: α and β

The specimen, a part or an individual element exemplifying the whole – in biology or life science it could be a sample of tissue, crystal, semi-conductor, catalyst, protein, etc, used for analysis and diagnosis in the microscope, but it could also be a piece of a plant, mineral, part, etc.

Figure 16: Double tilt holder [9]

Objective Lenses

The objective lens is one of the most important lenses in the transmission electron microscope, because it forms and a bit magnifies the initial image which is further magnified by the other lenses in the column. But the major use of the objective lens is focussing of the image. The lens must be highly energized (to obtain focal length of 1 – 2 mm), be free of astigmatism with minimal aberrations and contain some devices for correction of astigmatism (stigmators) to achieve required high resolution. Usually, it is water-cooled because of overheating. It should be also made from homogeneously blended metals and be symmetrical as much as possible. Most of the electrons passing through this lens are projected onto viewing screen. The more electrons going through any one point on the specimen, the brighter the image is generated. Also, the more dense or thick area of the specimen, the darker area will appear on the screen. Like in the condenser lenses also in objective lens, there is option to use different apertures. They are placed in the back focal plane under the specimen. The main function is to enhance contrast by trapping more of the peripherally deflected electrons. Apertures are not used just to control the amount of illumination but also depth of field. [8]

4.4.4. Imaging system

The Main parts of the imaging system are lenses. This system is involved in generation of image and its magnification and also projection of final image to viewing screen, camera or detectors. Diffraction and projective lenses are used for manipulation of image. Special part of imaging are projective lenses which are placed under and above specimen.

4.4.5. Detectors and cameras

In old microscopes, the image is projected onto viewing screen coated with phosphorescent zinc-activated cadmium sulphur. That method is usually used only for orientation and adjustment. Main measurement and observation is ensured by CMOS camera or other detectors, like HAADF, BF-DF or EELS detectors.

- **CMOS camera**

Camera an image sensor or imaging sensor is a sensor that detects and conveys the information that constitutes an image. It does so by converting the variable attenuation of light waves (as they pass through or reflect off objects) into signals, small bursts of current that convey the information. The waves can be light or other electromagnetic radiation. [31]

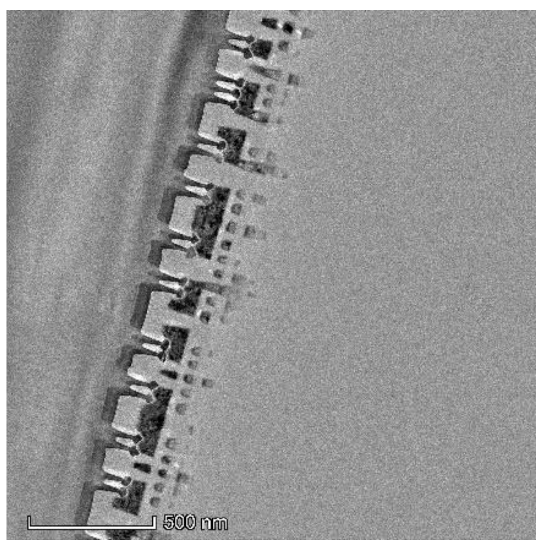

Figure 17: 13nm transistor displayed by CMOS camera

- **BF**

(bright field) this detector serves as bright field detector which is situated on optical axis of microscope. Detects nonscattered electrons.

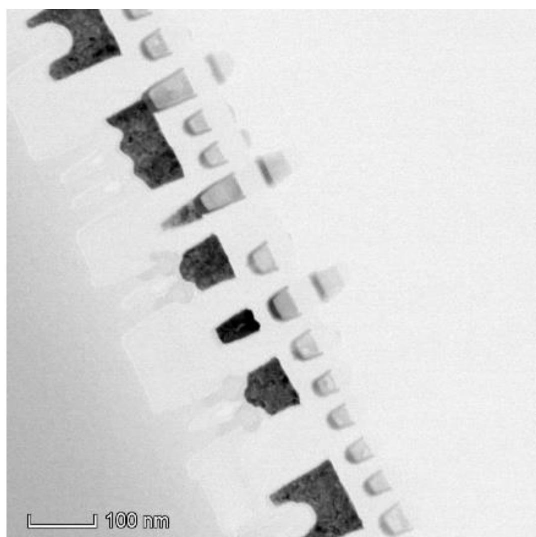

Figure 18: 13nm transistor displayed by BF detector

- **DF**

(dark filed) this detector serves as dark field detector. It has circular shape with hole in the middle which electrons go through. It follows that only scattered electrons are detected…

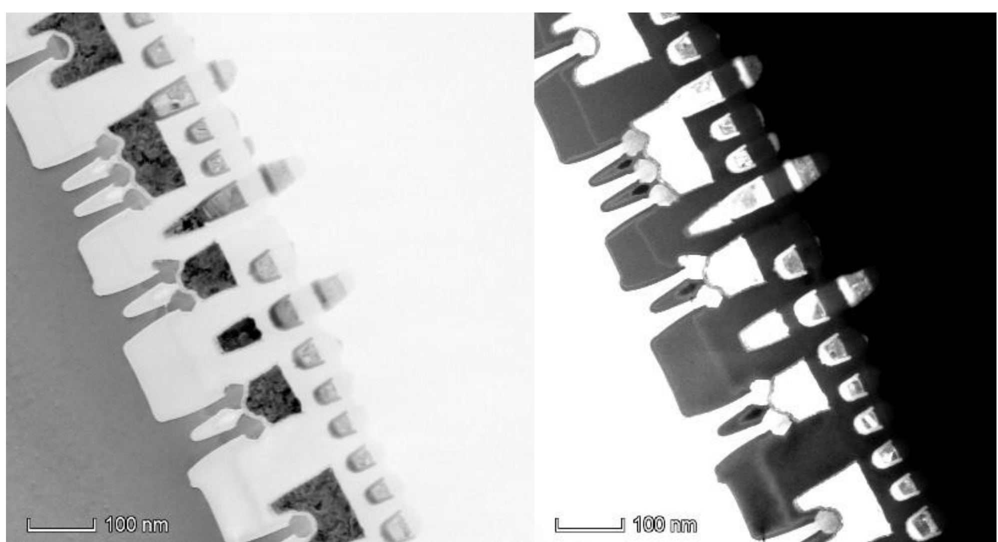

Figure 19: 13nm transistor displayed by DF2 and DF4 detectors

- **HAADF**

(high angle annular dark field) this type of detector is much bigger than normal DF and is situated away from optical axes. It detects the most scattered electrons. HAADF has the best contrast between listed detectors.

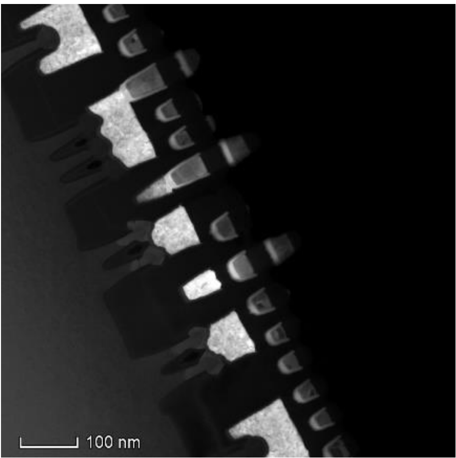

Figure 20: 13nm transistor displayed by HAADF detector

- **EELS** (Electron energy loss spectroscopy)

In electron energy loss spectroscopy (EELS) a material is exposed to a beam of electrons with a known, narrow range of kinetic energies. Some of the electrons will undergo inelastic scattering, which means that they lose energy and have their paths slightly and randomly deflected. The amount of energy loss can be measured via an electron spectrometer and interpreted in terms of what caused the energy loss. Inelastic interactions include phonon excitations, inter- and intra-band transitions, plasmon excitations, inner shell ionizations, and Cherenkov radiation. The inner-shell ionizations are particularly useful for detecting the elemental components of a material. For example, one might find that a larger-than-expected number of electrons comes through the material with 285 eV less energy than they had when they entered the material. This is approximately the amount of energy needed to remove an inner-shell electron from a carbon atom, which can be taken as evidence that there is a significant amount of carbon present in the sample. With some care, and looking at a wide range of energy losses, one can determine the types of atoms, and the numbers of atoms of each type, being struck by the beam. The scattering angle (that is, the amount that the electron's path is deflected) can also be measured, giving information about the dispersion relation of whatever material excitation caused the inelastic scattering. [31]

- **EDX** (electron dispersion spectroscopy)

To stimulate the emission of characteristic X-rays from a specimen, a high-energy beam of charged particles such as electrons or protons (see PIXE), or a beam of X-rays, is focused into the sample being studied. At rest, an atom within the sample contains ground state (or unexcited) electrons in discrete energy levels or electron shells bound to the nucleus. The incident beam may excite an electron in an inner shell, ejecting it from the shell while creating an electron hole where the electron was. An electron from an outer, higher-energy shell then fills the hole, and the difference in energy between the higher-energy shell and the lower energy shell may be released in the form of an X-ray. The number and energy of the X-rays emitted from a specimen can be measured by an energy-dispersive spectrometer. As the energies of the X-rays are characteristic of the difference in energy between the two shells and of the atomic structure of the emitting element, EDS allows the elemental composition of the specimen to be measured. [30]

EDS can be used to determine which chemical elements are present in a sample and can be used to estimate their relative abundance. The accuracy of this quantitative analysis of sample composition is affected by various factors. Many elements will have overlapping X-ray emission peaks (e.g., Ti Kβ and V Kα, Mn Kβ and Fe Kα). The accuracy of the measured composition is also affected by the nature of the sample. X-rays are generated by any atom in the sample that is sufficiently excited by the incoming beam. These X-rays are emitted in all directions (isotropically), and so they may not all escape the sample. The likelihood of an X-ray escaping the specimen, and thus being available to detect and measure, depends on the energy of the X-ray and the composition, amount, and density of material it has to pass through to reach the detector. Because of this X-ray absorption effect and similar effects, accurate estimation of the sample composition from the measured X-ray emission spectrum requires the application of quantitative correction procedures, which are sometimes referred to as matrix corrections. [30]

Figure 21: 13nm transistor displayed by HAADF detector and mapped by EDX

4.5. Microscope modes

The function of TEM is divided into two base mods, standard transmission mode TEM and scanning transmission mode STEM. Both these methods have different method of creation of image.

4.5.1. TEM mode

The TEM mode is primary viewing method of transmission electron microscope. Image of sample is created by beam of electrons which goes through sample enlarged by imaging system of microscope. Image is displayed by CCD camera on phosphor screen or CMOS camera at the bottom of microscope. Image resolution in TEM mode is determined by the energy of the electron beam also the time coherence and especially optical defects of magnetic lenses. In HR-TEM microscopy, the TEM display mode has one major disadvantage. Image is produced by the interference of the electron waves whose phase is affected by objective lens. The resulting image may not be simple to interpret it because some of its spatial frequencies can produce a positive contrast and part of the surround frequencies may cause reverse contrast.

4.5.2. STEM mode

The Stem mode is viewing mode similar to SEM microscopes. In place of the parallel illumination of the specimen, the electron beam is focused to the smallest point known as the probe. This probe then scans sample point by point on the part of the specimen that is defined by the field of view. In every single place, atom interact with beam. An electron that comes out of sample are captured by detectors. Image is created as composition of single pixels. Resolution of image depends on size of beam. At each point, the electron interacts with the solid part of sample. The electrons come out from the specimen are transferred to the detectors. The image is created by assigning one pixel in computer to point on the specimen. Image resolution in the STEM mode is determined by the size of the scanning probe and the setting of resolution for the given field of view on computer. The scanning probe is a projection of sources of electrons, then it determines its size primarily by the type of gun. Special case of STEM is HR STEM which can reach resolution under 1nm by This mode is especially sensitive to distortion.

5. Components sensitive to distortion

It is complicated to say which part of TEM is most valuable to distortion because this system is designed to be robust and pretty resistant. But its complexity is its main weak spot. We cannot forecast every single possibility that may cause problems. So, it's important to aim this research on few main components that can get harm from environment. In this thesis we focus on 2 main parts which are:

- Condenser and other lenses
- Electronics,

Besides distortion caused by main frequency of wireless communication system we should focus on distortion caused by power sources and low frequency unwanted signals caused by them because these frequencies can by displayed on final image, especial on HR STEM

5.1. GUN

On the very top of microscope is situated accelerator also known as a GUN. As a main part responsible of quality of beam just a little interference can cause problems, because every defect is transmitted to other parts of TEM.

5.2. Condensor

In the condenser are located beam deflection coil which are responsible for controlling beam which enter the sample and scanning move of beam in STEM mode. In some cases, beam deflection coils are responsible of interference itself and that leads us to premise that coils are sensitive to distortion.

5.3. Electronics

Electronics is serve as control unit of microscope. Every signal which influence microscope is processed in electronics. If some of kind of distortion enters electronics and is not suppressed will be transmitted to the system.

Ways to fight with distortion:

- Inner floating frame

It is designed to separate body of microscope from frame which can cause low frequency distortion from surrounding and floor. Inner frame floats on dumping which are filed by compressed air.

- Grounding

All conductive parts are connected via grounding vires to the Ground. Typology of connection is star and is designed to take away leaking current which can cause distortion with frequency of power sources.

- Cover

Covers together with grounding provides protection to electromagnetic waves from outside.

- Ferrites

They are commonly seen as a lump in a cable, called a ferrite bead, which helps to prevent high frequency electrical noise (radio frequency interference) from exiting or entering the equipment

6. FEI implementation

All subsystems and modules used in FEI products shall comply with legal, mandatory and functional safety and EMC requirements based on EU directives and standards and the regulatory compliance for foreign countries.

One of the purposes of distortion and influence measurement on main parameters of microscope caused by specified transceivers to this research is to provide information to create specification for wireless technology used on TEM microscope with respect to internal norms.

6.1. History of FEI

FEI Company (Field Electron and Ion Company, FEI) is an American company that designs, manufactures, and supports microscope technology. Headquartered in Hillsboro, Oregon, FEI has over 2,800 employees and sales and service operations in more than 50 countries around the world. Formerly listed on the NASDAQ, it is a subsidiary of Thermo Fisher Scientific.

Figure 22: FEI logo [42]

The FEI company was founded in 1971 as Field Electron and Ion Company by Dr. Lynwood W. Swanson, Mr. Noel A. Martin and Mr. Lloyd Swenson, as a supplier of electron and ion beam sources for field emission research and electron microscopy. The name was shortened to FEI Company in 1973. In 1978, Dr. J.H. Orloff, a research specialist in electrostatic optics for field emission ion and electron sources, joined the company as its fourth partner. Swanson was a professor of applied physics at the Oregon Graduate Center, and Orloff's doctoral adviser. FEI's introduction of the liquid metal ion source in 1981 led to its application in the semiconductor industry for mask repair and defect analysis. The current company was formed by the 1997 merger between FEI and Philips Electron Optics, and the 1999 acquisition of ion beam company Micrion. As such, the company can trace its roots in electron microscopy to the early commercial instruments produced by Philips Electron Optics in the 1940s.

On December 20, 2006, Philips Business Electronics International B.V. sold its shares of common stock in FEI Company reducing its shareholding in FEI to zero. In May 2011, the

company announced a second straight quarter of record revenue and profits, with the company totaling nearly $200 million in revenue for their second quarter. The company attributed the growth to a diversification of its clientele.

Figure 23: Thermo fisher scientific logo [25]

On May 27, 2016, Thermo Fisher Scientific Inc. announced its acquisition of FEI Company for 4.2 billion USD, which will commence in early 2017. At the time of the transaction, FEI had more than 2700 employees in over 20 countries. The FEI trademark is being phased out in favor of the Materials & Structural Analysis division of Thermo Fisher Scientific. [37]

6.2. Tested transceivers

On ideal state we can measure distortion of every frequency, but that will be complicated and unnecessary. In this case I sufficient to measure only that frequencies that can impact outcome of microscope. For example, distortion of very high frequencies has probably no impact on image Stem mode and in TEM mode as well.

In light of this knowledge we can narrow tests on function tests, like point analysis, info limit and HR STEM image analysis with tested transceivers.

6.2.1. Wi-FI

For testing distortion caused by Wi-Fi transceiver is suitable to use one which can provide 2,5 or 5 GHz signal. And with adjustable power output. As a suitable will be used AC1900 Dual-Band LTE Wi-Fi Modem Router with Parental Controls and Guest Network

Figure 24:Used Asus WIFI router [38]

6.3. Tests

As it was mentioned before the testing part will be narrowed to function test which can give as results about distortion caused by transceivers and their influence to parameters of microscope.

6.3.1. Contrast transfer function (information limit)

Contrast transfer theory provides a quantitative method to translate the exit wavefunction to a final image. Part of the analysis is based on Fourier transforms of the electron beam wavefunction. When an electron wavefunction passes through a lens, the wavefunction goes through a Fourier transform. [39]

The contrast transfer function determines how much phase signal gets transmitted to the real space wavefunction in the image plane. As the modulus squared of the real space wavefunction gives the image signal, the contrast transfer function limits how much information can ultimately be translated into an image. The form of the contrast transfer function determines the quality of real space image formation in the TEM. [39]

6.3.2. Point spread function (point analysis)

Diffraction of light, which determines the microscope's resolution limit, blurs out any point-like object to a certain minimal size and shape called the Point Spread Function (PSF). The point spread function (PSF) describes the response of an imaging system to a point source or point object. A more general term for the PSF is a system's impulse response. The degree of spreading (blurring) of the point object is a measure for the quality of an imaging system. [40]

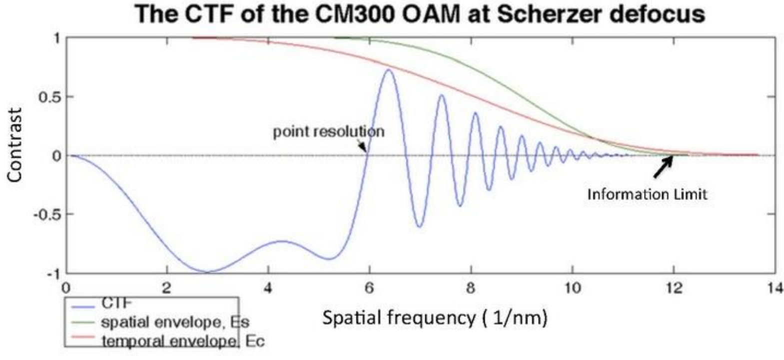

Figure 25: Image of contrast transfer function [39]

6.3.3. HR STEM resolution

This test provides information about maximal resolution of microscope as I mention before in high performance microscopes is measured on silicon mono crystal. HR STEM is most complicated function that modern TEM can provide

7. Measurement

From devices described above is used Wi-Fi as most universal and suitable communication method for our purposes. As is mentioned before there will be 3 types of measurements: Information limit, point analysis and STEM analysis. Which can provide information about function and parameters of microscope.

All of these measurements need to be done on finalize microscope and take plenty of time. There is problem with contamination in these types of measurement. When the specimen is exposure to beam of electrons for quite long time there is possibility that some impurities can be transmitted on. That can cause lowering of resolution as a result of increasing thickness of sample. Drift of sample can by problem too and is manifested as cut off on FFT image.

Drift can ususaly lowered in few tens of minutes, but exposuire that long cause contamination as we can se on. Contamination can by lowered by using cold trap near the sample. Cold trap is a device that condenses all vapors except the permanent gases into a liquid or solid and is cooled by liquid nitrogen. Every few days cryo cicle shoud be done which contains of heating cold trap and evaucaitng unleashed inpurities by TMP.

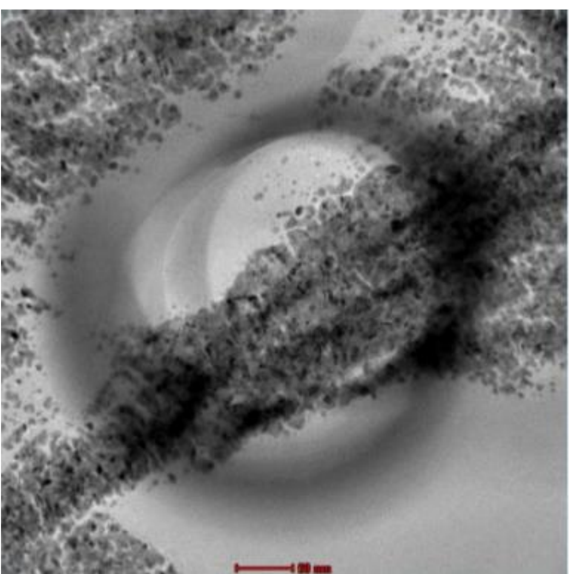

Figure 26: Example of Contamination caused by long exposure during measurement

7.1. Information limit

The information limit is a measure of the highest frequency that is transferred through the optical system. During exposure of the CCD the image is shifted ~2nm to produce Young's fringes in the FFT. The extent of the fringes is a measure of the information limit. For this measurement gold on carbon is used. The red circle indicates resolution limit of this measurement. Limit of Talos microscope is 0.12 nm. For proper measurement is necessary to properly adjust conditions. It is important to minimalize aberrations such an astigmatism and coma and external sources of distortion.

Figure 27 servers as an example of satisfactory image of information limit, the Young´s fringes exceed red circle in every direction no cut-off is visible.

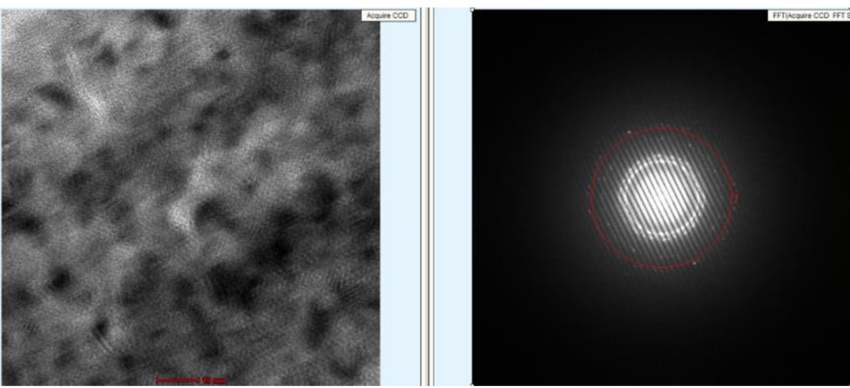

Figure 27: Satisfactory information limit

Figure 28 servers as an example of distortion in image of information limit, the Young´s fringes exceed red circle in two direction which so resolution of image is sufficient but cut-off of FFT suggests distortion or problem with optics.

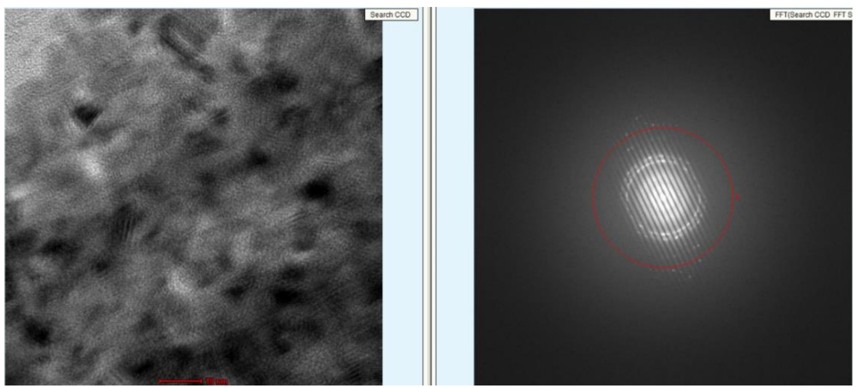

Figure 28: Unsatisfactory information limit

Table 3: Information limit measurement 1/4

Ch	location of transmitter		Description
	electronics	body	
1			Measurement with data transmitting on channel 1. Test passed. Resolution of test exceed limit in all directions
2			Measurement with data transmitting on channel 2. Test passed. Resolution of test exceed limit in all directions
3			Measurement with data transmitting on channel 2. Test did not passed. Resolution sufficient, cut-off on FFT appeared See (*1)

*1 This cut-off appeared during changing of channel. There is possibility of connection between changing state of transmitter and distortion of analysis. However, as I mentioned before, this type of measurement is extremely sensitive to external vibrations. Future measurement is required.

Table 4: Information limit measurement 2/4

Ch	location of transmitter		Description
	electronics	body	
4			Measurement with data transmitting on channel 4. Test passed. Resolution of test exceed limit in all directions
5			Measurement with data transmitting on channel 5. Test passed. Resolution of test exceed limit in all directions
6			Measurement with data transmitting on channel 6. Test passed. Resolution of test exceed limit in all directions
7			Measurement with data transmitting on channel 7. Test passed. Resolution of test exceed limit in all directions

Table 5: Information limit measurement 3/4

Ch	location of transmitter		Description
	electronics	body	
8			Measurement with data transmitting on channel 8. Test passed. Resolution of test exceed limit in all directions
9			Measurement with data transmitting on channel 9. Test did not passed. Resolution sufficient, cut-off on FFT appeared See *2
10			Measurement with data transmitting on channel 10. Test passed. Resolution of test exceed limit in all directions

*2 This cut-off appeared during start of data transmitting. There is possibility of connection between changing state of transmitter and distortion of analysis. However, as I mentioned before, this type of measurement is extremely sensitive to external vibrations. Future measurement is required.

Table 6: Information limit measurement 4/4

Ch	location of transmitter		Description
	electronics	body	
11			Measurement with data transmitting on channel 11. Test passed on both measurement places. Resolution of test exceed limit in all directions
12			Measurement with data transmitting on channel 12. Test passed. Resolution of test exceed limit in all directions
13			Measurement with data transmitting on channel 13. Test passed. Resolution of test exceed limit in all directions

7.2. Point resolution

The point resolution is a measure of the resolution where no lower frequencies are blocked or have an opposite sign. The distance from the centre to the first dark ring in the diffractogram is a measure of the point resolution. Defocus is Scherzer. For our measurement graphitized carbon was used. Sample need to by extremely thin to get proper resolution. Transvers was located on to places to for this measurement, near the body of microscope and near the electronics

The red line indicates resolution limit of this measurement. Limit of Talos microscope is 0.25 nm. For proper measurement is necessary to specifically adjust conditions, which are similar to information limit measurement. Point analysis is more sensitive to aberration than information limit. In many cases is nearly impossible to get proper conditions due to coma.

Figure 29 servers as an example of satisfactory image of point analysis. The distance from the centre to the first dark ring in the diffractogram achieve or exceed limit of 0,25nm. FFT image is sharp in all directions. Second circle is fully visible which indicates possibility of better result

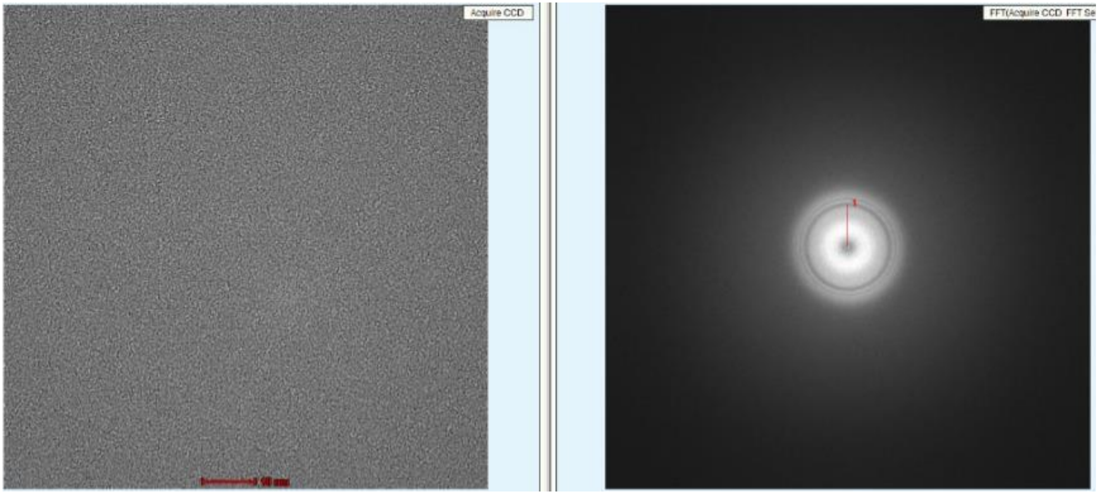

Figure 29: Satisfactory point analysis

Figure 30 servers as an example of satisfactory image of point analysis. The distance from the centre to the first dark ring in the diffractogram achieve or exceed limit of 0,25nm. FFT image is sharp in all directions. Second circle is fully visible which indicates possibility of better result

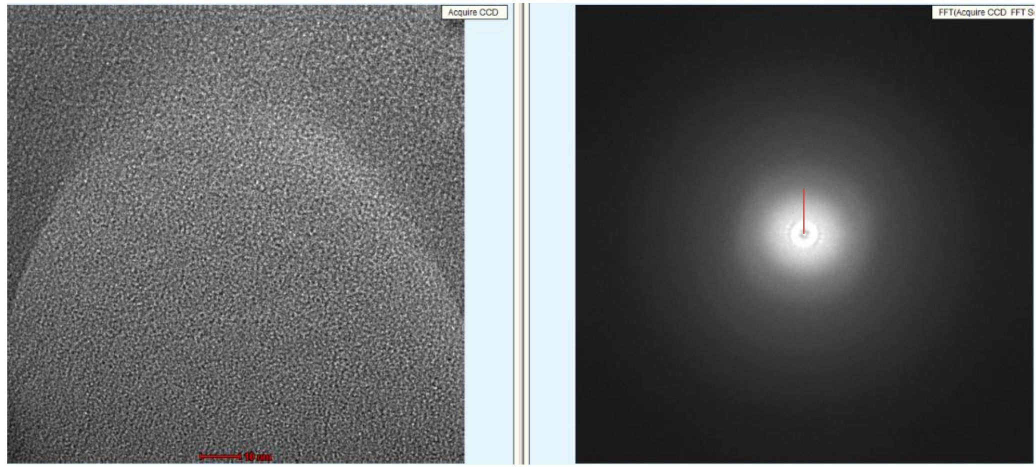

Figure 30: Unsatisfactory point analysis

Table 7: Point analysis measurement 1/4

Ch	location of transmitter		Description
	electronics	body	
1			Measurement with data transmitting on channel 1. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected.
2			Measurement with data transmitting on channel 2. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected
3			Measurement with data transmitting on channel 3. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected
4			Measurement with data transmitting on channel 4. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected

Table 8: Point analysis measurement 2/4

Ch	location of transmitter		Description
	electronics	body	
5			Measurement with data transmitting on channel 5. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3
6			Measurement with data transmitting on channel 6. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3
7			Measurement with data transmitting on channel 7. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3
8			Measurement with data transmitting on channel 8. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3

Table 9: Point analysis measurement 3/4

Ch	location of transmitter		Description
	electronics	body	
9			Measurement with data transmitting on channel 9. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3
10			Measurement with data transmitting on channel 10. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3
11			Measurement with data transmitting on channel 11. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3
12			Measurement with data transmitting on channel 12. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3

Table 10: Point analysis measurement 4/4

Ch	location of transmitter		Description
	electronics	body	
13			Measurement with data transmitting on channel 13. Test passed. Resolution of tests fulfilled limit in all directions, astigmatism and other aberrations are corrected. Defocus is out of limit due to drift see *3

*3 proper defocus is sufficient for point analysis. Due to drift in z axis the value of ideal defocus has changed.

7.3. STEM

STEM as the most complicated viewing method is most sensitive to distortion. Plenty of condition have to be fulfil to get good high-resolution stem image. This method is especially sensitive to proper align of electron beam and aberrations as well. Highly experienced user is needed to get proper image.

For proper orientation of specimen are Kikuchi lines used. Kikuchi lines pair up to form bands in electron diffraction from single crystal specimens, there to serve as "roads in orientation-space" for microscopists not certain at what they are looking. In transmission electron microscopes, they are easily seen in diffraction from regions of the specimen thick enough for multiple scattering. Unlike diffraction spots, which blink on and off as one tilts the crystal, Kikuchi bands mark orientation space with well-defined intersections (called zones or poles) as well as paths connecting one intersection to the next.

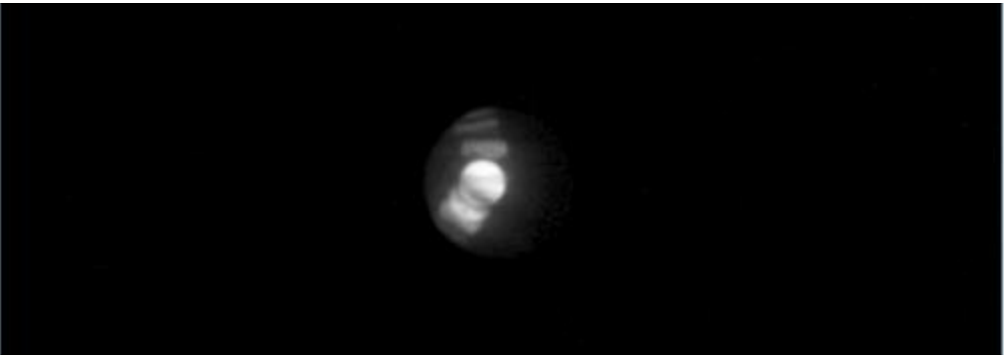

Figure 31: Kikuchi lines of misalign α tilt

Kikuchi lines are formed in diffraction patterns by diffusely scattered electrons, e.g. as a result of thermal atom vibrations. The main features of their geometry can be deduced from a simple elastic mechanism proposed in 1928 by Seishi Kikuchi

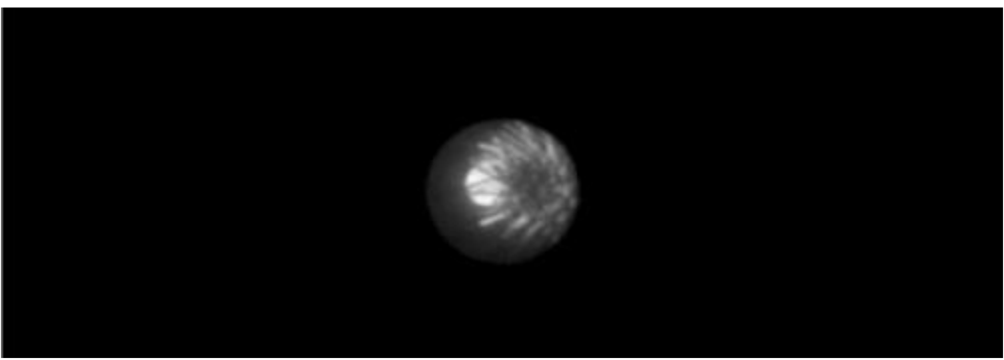

Figure 32: Kikuchi lines of almost aligned α tilt

Figure 33 serves as example of satisfactory image of silicon. There is no distortion seen in the FFT image. Resolution of image exceeds limit of 1.6nm as a proof serves “stars” on FFT analysis (red circles) and sharpness of image Each point (star) in FFT image stands for repetitive signal in STEM image and hold place dependable on frequency.

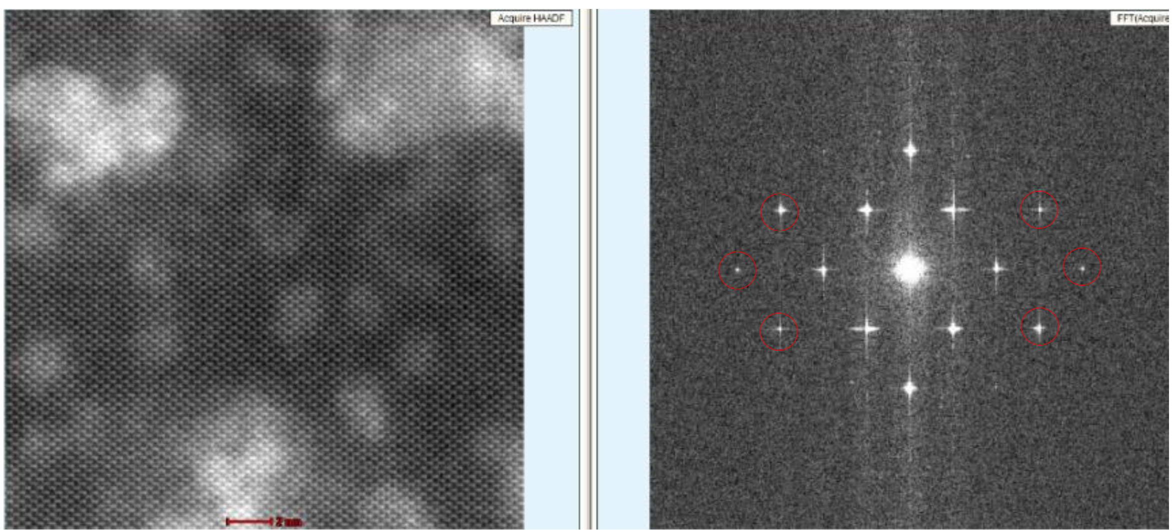

Figure 33: Image of silicon magnified by 5.1M with good resolution and without distortion

Figure 34 serves as example of no satisfactory image of silicon. Resolution of image exceeds limit of 1.6nm as a proof serves “stars” on FFT analysis image (red circles). There is distortion seen in the FFT image. As a proof serves dots (blue circle) near main stars. These point stand as an image of 1kHz distortion caused by TMP.

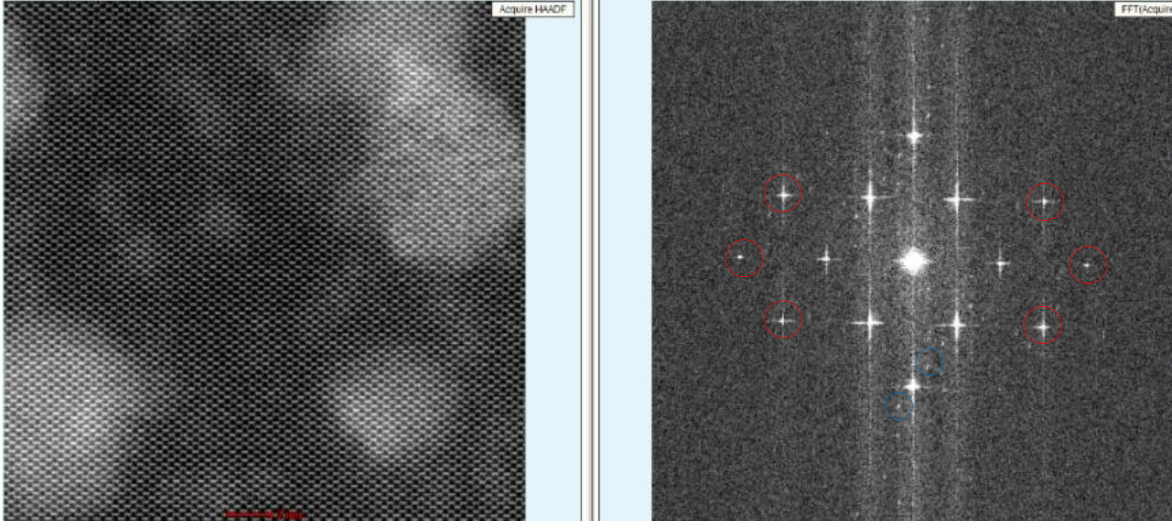

Figure 34: Image of silicon magnified by 5.1M with good resolution and with distortion

Figure 35 serves as example of no satisfactory image of silicon. Despite of suitable resolution in FFT image is blurred. That may by caused by contamination (white clouds in image)

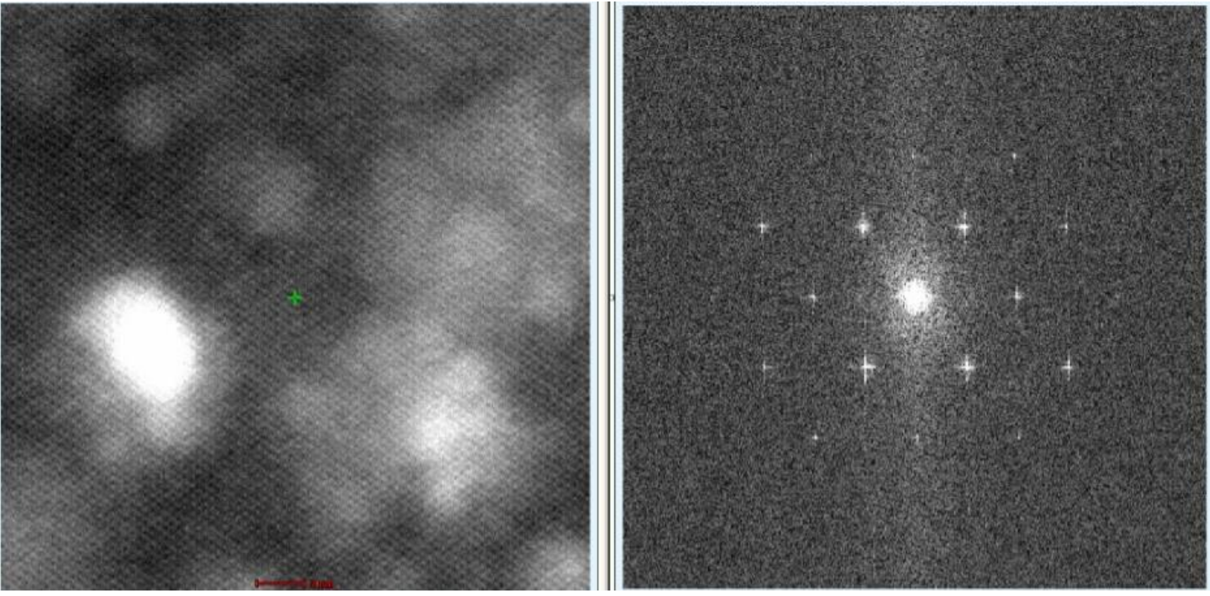

Figure 35: Image of silicon magnified by 5.1M (blurred)

Figure 36 serves as example of no satisfactory image of silicon. Image seems sharp but in FFT are seen unspecified dots which stands for distortion of unknown frequencies.

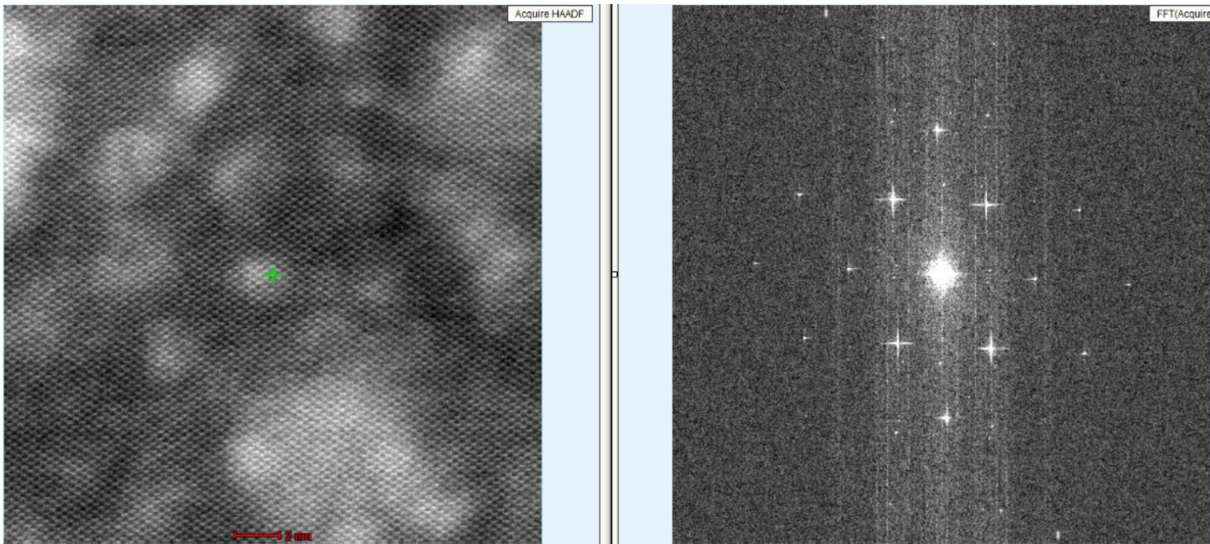

Figure 36: Image of silicon magnified by 5.1M (high distortion)

Each point (star) in FFT image stands for repetitive signal in STEM image and hold place dependable on frequency. Some of the points are easy evaluable like 1kHz caused by TMP some of them needs to be evaluate by SQT analysis.

Table 11: STEM resolution measurement 1/4

Ch	image	FFT	Description
1			Measurement with data transmitting on channel 1 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible. Light distortion by TMP is visible
2			Measurement with data transmitting on channel 2 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible. Distortion by TMP and other sources visible see *4
3			Measurement with data transmitting on channel 3 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible. Distortion by TMP visible see *4
4			Measurement with data transmitting on channel 4 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible

*4 distortion visible in FFT of HR STEM is caused by low frequencies. In most cases is caused by vibration of TMP, because of stable frequency of TMP which is 1000Hz is this type of distortion easy to localize. And can by removed by exchange of TMP.

Table 12: STEM resolution measurement 2/4

Ch	image	FFT	Description
5			Measurement with data transmitting on channel 5. Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible. Light distortion by TMP is visible
6			Measurement with data transmitting on channel 6 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible. Distortion by TMP and other sources visible see *4
7			Measurement with data transmitting on channel 7 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible. Heavy distortion visible see *4
8			Measurement with data transmitting on channel 8 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible

Table 13: STEM resolution measurement 3/4

Ch	image	FFT	Description
9			Measurement with data transmitting on channel 9 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible
10			Measurement with data transmitting on channel 10 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible
11			Measurement with data transmitting on channel 11 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible
12			Measurement with data transmitting on channel 12 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible

Table 14: STEM resolution measurement 4/4

Ch			Description
	image	FFT	
13			Measurement with data transmitting on channel 13 Resolution of image achieved. Image of silicon is sharp pairs of silicon atoms clearly visible

*4 distortion visible in FFT of HR STEM is caused by low frequencies. In most cases is caused by vibration of TMP, because of stable frequency of TMP which is 1000Hz is this type of distortion easy to localize. And can by removed by exchange of TMP.

*5 Other frequency's visible in FFT is much more complicated to localize, for example 50 Hz and their multiples is almost impossible to localize completely. This distortion is usually caused by some type of source which has to be replaced.

*6 extreme sensitivity of microscope to low frequency distortion is shown by distortion caused by SF6 probes situated near TEM.

Not every frequency is recognizable on FFT. For these cases is SQT analysis needed. Parameters and function of SQT analysis is confidential and cannot be published in this thesis.

Another way of distortion measurement was used, due to FEI policy pair image with distortion graph is not allowed. Figures 36 and 37 serves as examples of distortion graphs.

Measurement of distortion by this method is limited to 5000 Hz. in figure 37 is clearly seen a distortion. For example, you can see peak on 1000 Hz and some their harmonic multiples. Proper align of STEM image is needed. Every imprecision in align my cause change accuracy of measurement.

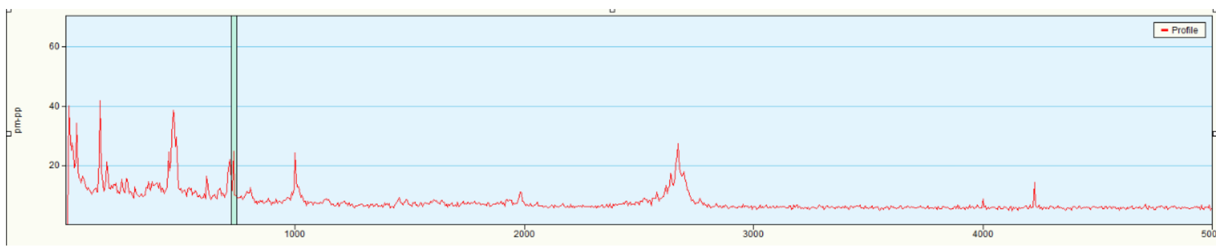

Figure 37: Frequency analysis of HR-STEM image of silicon nanocrystal with distortion

None of the STEM image prove connection between distortion in image and transmitting data by Wi-Fi near TEM. But it is hard to positively made conclusion about distortion. STEM imaging is enough sensitive that distortion which can by caused by too much outdoor sources that is hard to find pattern.

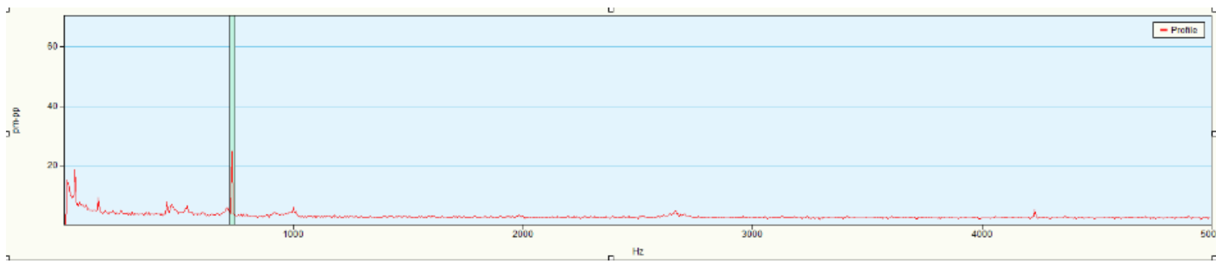

Figure 38: Frequency analysis of HR-STEM image of silicon nanocrystal without distortion

8. Conclusion

This master thesis is divided to 3 main parts. First part analyses and describe available wireless communication technologies usable for transmission electron microscope. Second part describes theory of transmission electron microscopy as well as its parts as a gun, coils and detectors. And final part describes measurements of parameters in connection with possible distortion caused by transmitters.

Thesis was focused on 200 kV transmission electron microscope known as F200X Talos manufactured by FEI company. Measurement was carried out on two microscopes. On first one was tested TEM parameters such as information limit and point analysis. STEM went on second one. Tested microscopes were situated in manufacturing hall in Brno. Two microscopes had to be used to not influence production.

Measurement of information limit did not provide results which can confirm clear influence of transmitter to parameters of microscope. However light distortion was observed. It was probably caused by changing state of transceiver such as start of transmission, exchange of channel and etc. and had to be analyse on the future. Measurement of point analysis was not affected by distortion caused by transceiver at all.

Making proper HR STEM image is so difficult that separate distortion caused by environment and tested transceiver is practically impossible. In case of strong low frequency distortion is possible that this low frequency can hide other. In measurement of STEM was not found connection between parameters of STEM and tested transceiver.

In the future is possible to measure influence of other types of devices mentioned before, measure influence of transceiver build in the electronics of TEM.

The main focus will be the regulatory compliance for foreign countries. Any wireless communication on the principle of forced emission (Wi-Fi, RFID, etc.) is a major problem in terms of global compliance and regulation. Main issue is export to non-EU or US countries, each country need specific documentation of EMC certification

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