CHAPTER 2

THIN FILM GROWTH AND CHARACTERIZATION
TECHNIQUES

2.1  THIN FILMS

A thin film is a layer of material ranging from fractions of a nanometer (monolayer) to several micrometers in thickness. A thin film, as its name implies, is a layer with a high surface-to-volume ratio. Thin films are extensively used in wafer fabrication, and can be a resistor, a conductor, an insulator, or even a semiconductor. Thin films can be deposited on a substrate by thermal growing or by vapor deposition. Thins films behave differently from bulk materials of the same chemical composition in several ways. For instance, thin films are sensitive to surface properties while bulk materials generally aren't. Thin films are also relatively more sensitive to thermo-mechanical stresses.

The integrity of thin films is influenced by the quality of its adhesion to and conformal coverage of the underlying layer, residual or intrinsic stresses after deposition, and the presence of surface imperfections such as pinholes. The adhesion of a thin film to the substrate or underlying layer is of great concern in ensuring the reliability of the thin film. A thin film that is initially adhering to the underlying layer but lifts off after the device is subjected to thermo-mechanical stresses can result in field failures. Reliable thin film adhesion depends greatly on the cleanliness of the surface upon which the film is deposited. Optimum substrate roughness also affects thin film adhesion. A very smooth substrate decreases adhesion tendency. A very rough substrate on the other can result in coating defects, which can also lead to thin film adhesion failures.
Regardless of the deposition process, thin films always end up with an intrinsic stress which can either be tensile or compressive. High residual stresses can lead to adhesion problems, corrosion, cracking, and deviations in electrical properties. Thus, proper deposition is critical to minimize intrinsic stresses in thin films.

2.1.1 Modes of thin film growth

Formation of a thin film takes place via nucleation and growth processes. The experimental and theoretical studies of a thin film growth can be presented as follows:

1. The material or component to be deposited on the substrate, lose their velocity component normal to the substrate (provided the incident energy is not too high) and are physically adsorbed on the substrate surface.

2. The adsorbed species are not in thermal equilibrium with the substrate initially and move over the substrate surface. In this process they interact among themselves, forming bigger clusters.

3. The clusters or the nuclei, as they are called, are thermodynamically unstable and may tend to desorbing time, depending on the deposition parameters. If the deposition parameters are such that a cluster collides with other adsorbed species before getting desorbed, it starts growing in size. After reaching a certain critical size, the cluster becomes thermodynamically stable and the nucleation barrier is said to have been overcome. This is called the nucleation stage.

4. The critical nuclei grow in number as well as in size until a saturation nucleation density is reached. The nucleation density and the average
nucleus size depend on a number of parameters such as the energy of the impinging species, the rate of impingement, the activation energies of adsorption, desorption, thermal diffusion, and the temperature, topography, and chemical nature of the substrate. A nucleus can grow both parallel to the substrate by surface diffusion of the adsorbed species, and perpendicular to it by direct impingement of the incident species. In general, however, the rate of lateral growth at this stage is much higher than the perpendicular growth. The grown nuclei are called islands.

5. The next stage in the process of film formation is the coalescence stage, in which the small islands start coalescing with each other in an attempt to reduce the substrate surface area. This tendency to form bigger islands is termed agglomeration and is enhanced by increasing the surface mobility of the adsorbed species, for example: increasing the substrate temperature. In some cases, formation of new nuclei may occur on areas freshly exposed as a consequence of coalescence.

6. Larger islands grow together, leaving channels and holes of uncovered substrate. The structure of the films at this stage changes from discontinuous island type to porous network type. Further deposition and hence the resultant filling of the channels and holes forms a completely continuous film.

The growth process thus may be summarized as consisting of a statistical process of nucleation, surface-diffusion controlled growth of the three-dimensional nuclei, and formation of a network structure and its subsequent filling to give a continuous film. Depending on the thermodynamic parameters of the deposit and the substrate surface, the initial nucleation and growth stages may be described as:
a. Island type, called Volmer-Weber type
b. Layer type, called Frank-van der Merwe type, and
c. Mixed type, called Stranski-Krastanov type.

All this 3 types are illustrated in figure 2.1.

**Figure 2.1**: Thin film growth modes- (a) Volmer Weber, (b) Frank-van der Merwe and (c) Stranski-Krastanov

### 2.1.1.1 Volmer-Weber growth

In VW growth, adatom-adatom interactions are stronger than those of the adatom with the surface, leading to the formation of three-dimensional adatom clusters or islands. Growth of these clusters, along with coarsening, will cause rough multi-layer films to grow on the substrate surface.
2.1.1.2 Frank-van der Merwe growth

In FM growth, adatoms attach preferentially to surface sites resulting in atomically smooth, fully formed layers. This layer-by-layer growth is two dimensional, indicating that complete films form prior to growth of subsequent layers.

2.1.1.3 Stranski-Krastanov growth

Also known as 'layer-plus-island growth', the SK mode follows a two-step process: initially, complete films of adsorbates, up to several monolayers thick, grow in a layer-by-layer fashion on a crystal substrate. Beyond a critical layer thickness, which depends on strain and the chemical potential of the deposited film, growth continues through the nucleation and coalescence of adsorbate 'islands'. This kind of growth is an intermediary process characterized by both 2D layer and 3D island growth. Transition from the layer-by-layer to island-based growth occurs at a critical layer thickness which is highly dependent on the chemical and physical properties, such as surface energies and lattice parameters, of the substrate and film.

2.1.2 Defects in thin films

Under special conditions, the crystallographic orientations and the topographical details of different islands are randomly distributed, so that when they touch each other during growth, grain boundaries and various point and line defects are incorporated into the film due to mismatch of geometrical configurations and crystallographic orientations. If the grains are randomly oriented, the films show a ring-type diffraction pattern and are said to be polycrystalline. If the grain size is small (less than 20 Å), the films show halo-type diffraction patterns similar to those exhibited by amorphous structures highly disordered. Even if the orientation of different islands is the same throughout, a single-crystal film is not obtained. Instead, the film consists of single-crystal
grains oriented parallel to each other and connected by low-angle grain boundaries. These films show diffraction patterns similar to those of single crystals and are called epitaxial single-crystal films.

Besides grain boundaries, epitaxial films may also contain other structural defects such as dislocation lines, stacking faults, micro twins, and twin boundaries, multiple-positioning boundaries, and minor defects arising from aggregation of point defects (for example, dislocation loops, stacking faults, and tetrahedral and small dot like defects). Note that defects such as stacking faults and twin boundaries occur much less frequently in polycrystalline films. Dislocations with a density of $10^{10}$ to $10^{11}$ lines/cm$^2$ are the most frequently encountered defects in polycrystalline films and are largely incorporated during the network and whole stages due to displacement misfits between different islands. Some other mechanisms which may give rise to dislocations in thin films are

1. Substrate film lattice misfit,
2. The presence of inherent large stresses in thin films, and
3. Continuation into the film of the dislocations apparently ending on the substrate surface.

After a continuous film is formed, anisotropic growth takes place normal to the substrate in the form of cylindrical columns. The initial nucleation density determines the lateral grain size, or crystallite size.

However, if re-crystallization takes place during the coalescence stage, the lateral grain size is larger than the average separation of the initial nuclei, and the average number of grains per unit area of the film is less than the initial nucleation density. The grain size normal to the substrate is equal to the film thickness. For thicker films, nucleation takes place at the surface of previously grown grains, and
each vertical column grows multi granularly with possible deviations from normal growth. Figure 2.2 shows various defects incorporated into thin film systems.

Figure 2.2: A schematic diagram showing the incorporation of defects in thin film during synthesis.

2.1.3 Factors affecting film growth

There are certain factors which affects the growth of a thin film over a substrate. Few of them are listed in figure 2.3.
2.1.3.1 Surface Roughness and Density

Under conditions of a low nucleation barrier and high super saturation, the initial nucleation density is high and the size of the critical nucleus is small. This results in fine-grained, smooth deposits which become continuous at small thicknesses. On the other hand, when the nucleation barrier is large and the super saturation is low, large but few nuclei are formed, resulting in coarse-grained...
rough films which become continuous at relatively large thicknesses. High surface mobility, in general, increases the surface smoothness of the films by filling in the concavities.

Density is also an important parameter of physical structure. It must be known for the determination of the film thickness by gravimetric methods. A general behavior observed in thin films is a decrease in the density with decreasing film thickness. This is qualitatively illustrated in figure 2.4.

Surface roughness is also essentially related to the modes of film growth described earlier. The Frank-van der Merwe mode provides the smooth surface and Volmer-Weber mode provides the rough surface. The roughness is analyzed by computer modeling the film growth. The strains due to the thermal expansion mismatch between a film and its substrate affect the surface microstructure and the roughness. In a heteroepitaxial film, the density will change due to the deformation of the lattice structure.

Figure 2.4: Qualitative variation of (a) the roughness factor and (b) the film density as a function of film thickness.
2.1.3.2 Adhesion

Adhesion, also called bonding of a film to the substrate is strongly dependent on the chemical nature, cleanliness, and the microscopic topography of the substrate surface. This adhesion is better for higher values of

(1) Kinetic energy of the incident species,

(2) Adsorption energy of the deposit, and

(3) Initial nucleation density.

The presence of contaminants on the substrate surface may increase or decrease the adhesion depending on whether the adsorption energy is increased or decreased, respectively. Also, the adhesion of a film can be improved by providing more nucleation centers on the substrate, for instance, by using a fine-grained substrate or a substrate pre coated with suitable materials. Loose and porous deposits formed under conditions of high super saturation and poor vacuum are less adherent than compact deposits. The deposited films include internal stress during film growth. The elastic energy is stored in the films due to the stress.
2.2 EXPERIMENTAL AND ANALYTICAL TECHNIQUES

The various instruments used for synthesis and characterization of the samples in the experiments detailed in this work are briefly described in this section. The instruments used are:

- Physical Vapor Deposition System with E Beam Evaporator
- Scanning Probe Microscope
- Vibrating Sample Magnetometer
- X-Ray diffractometer
- Scanning Electron Microscope with EDS

The specific configuration and a brief description of each of these systems are given in the subsections below.

2.2.1 Physical Vapor Deposition System with E Beam Evaporator

Physical vapor deposition (PVD) is a term used to describe a variety of vacuum deposition techniques used to deposit thin films by the condensation of a vaporized form of the material onto various surfaces (e.g., onto semiconductor wafers). The coating method involves purely physical processes such as high temperature vacuum evaporation or plasma sputter bombardment rather than involving a chemical reaction at the surface to be coated as in chemical vapor deposition. PVD techniques are also commonly used for the purpose of fabrication extreme thin films like atomic layers for research purposes. A good example is the mini e-beam evaporator which can deposit monolayers of virtually all materials with melting points up to 3500°C.
Electron Beam Physical Vapor Deposition or EBPVD is a form of physical vapor deposition in which a target anode is bombarded with an electron beam given off by a charged tungsten filament under high vacuum. The electron beam causes atoms from the target to transform into the gaseous phase. These atoms then precipitate into solid form, coating everything in the vacuum chamber (within line of sight) with a thin layer of the anode material.

Figure 2.5: Photograph of BC 300 Box Coater system
The BC300 box coater system procured from HIND HIVAC, Bangalore is a versatile PVD system capable of supporting both electron beam and thermal evaporators. Pumped by 550 l/s Turbo molecular pump (Varian Inc.) and support by a rotary vane pump, the system can be pumped down to maximum vacuum of $2 \times 10^{-7}$ mbar. Equipped with a four source selector, the system is capable to sequential evaporation of up to four metals/alloys without breaking the vacuum. The system also boasts of a substrate heater (800°C), a radiant heater (200°C) and a large rotary drive capable of handling industrial grade samples.

The vacuum is measured by use of two digital Pirani gauges and one Inverted Magnetron Gauge of high vacuum measurement. The electron beam gun is typical 270° bent beam gun which ensures least sample and filament contamination.

### 2.2.2 RF Sputter Deposition System

Sputter deposition is a physical vapor deposition (PVD) method of depositing thin films by sputtering. This involves ejecting material from a "target" that is a source onto a "substrate" such as a silicon wafer. Re-sputtering is re-emission of the deposited material during the deposition process by ion or atom bombardment. Sputtered atoms ejected from the target have a wide energy distribution, typically up to tens of eV (100,000 K). The sputtered ions (typically only a small fraction of the order of 1% - of the ejected particles are ionized) can ballistically fly from the target in straight lines and impact energetically on the substrates or vacuum chamber (causing resputtering). Alternatively, at higher gas pressures, the ions collide with the gas atoms that act as a moderator and move diffusively, reaching the substrates or vacuum chamber wall and condensing after undergoing a random walk. The entire range from high-energy ballistic impact to low-energy thermalized motion is accessible by changing the chamber gas pressure. The sputtering gas is often an inert gas such as argon. For efficient momentum transfer, the atomic weight of the sputtering gas should be approximately equal to the atomic weight of the target, so
for sputtering light elements neon is preferable, while for heavy elements krypton or xenon are used. Reactive gases can also be used to sputter compounds. The compound can be formed on the target surface, in-flight or on the substrate depending on the process parameters. The possibility of many parameters that can control sputter deposition make it a complex process, but also allow experts a huge degree of control over the growth and microstructure of the film.

Sputtering sources often consists of magnetrons that utilize strong electric and magnetic fields to localize charged plasma particles close to the surface of the sputter target. Under the influence of a magnetic field, electrons follow helical paths around magnetic field lines undergoing more ionizing collisions with gaseous neutral species near the target surface than would otherwise occur. (As the target material is depleted, a "racetrack" erosion profile may appear on the surface of the target). The extra sputter gas ions (argon ions in usual cases) created as a result of these collisions leads to a higher rate of deposition. This also indicates that the plasma can be sustained at a lower pressure. The sputtered atoms are neutral and so are unaffected by the magnetic field trap. Charge build-up on insulating targets can be avoided with the use of RF sputtering where the sign of the anode-cathode bias is varied at a high rate (commonly 13.56 MHz) [42]. RF sputtering produces highly insulating oxide films but with the added expense of RF power supplies and impedance matching networks. Stray magnetic fields leaking from ferromagnetic targets also hinder the sputtering process. Specially designed sputter guns with unusually strong permanent magnets must often be used in compensation. Figure 2.6 depicts a typical plasma plume originating in a sputtering target.
The RF magnetron sputter deposition system used for this work is a homemade system which was built during the tenure of this Ph.D. dissertation. An RF power supply of 400W was used for powering the deposition system. The magnetron setup was purchased from Kurt J. Lesker Company. The system was subjected to various trial runs and the deposition parameters were optimized before being used for the experiments detailed in this work.

Figure 2.6: Plasma plume in a RF sputter deposition system
2.2.3 Scanning Probe Microscope

Scanning Probe Microscopy (SPM) comprises a family of techniques in which a sharp probe (cover) on a cantilever is precisely scanned across a surface. The force between the tip and sample results in the deflection of the cantilever. The motion is followed with a laser beam that is reflected by the cantilever. In this way a small change in the tip position is translated to a larger movement of a laser spot. When the reflected beam changes position, the output of a photo detector changes proportional to the deflection of the cantilever. Motions smaller than 1 nanometer is routinely measured with this method. As a result, a surface can be imaged by scanning the tip and maintaining the force between the probe tip and the sample surface. Using different probes it is possible to examine a variety of forces - i.e. van-der Waals, friction, magnetic or electrical.

2.2.3.1 Atomic force microscopy (AFM)

Atomic force microscopy (AFM) or scanning force microscopy (SFM) is a very high-resolution type of scanning probe microscopy, with demonstrated resolution on the order of fractions of a nanometer, more than 1000 times better than the optical diffraction limit. The precursor to the AFM, the scanning tunneling microscope, was developed by Gerd Binnig and Heinrich Rohrer in the early 1980s at IBM Research - Zurich, a development that earned them the Nobel Prize for Physics in 1986. Binnig, Quate and Gerber invented the first atomic force microscope (also abbreviated as AFM) in 1986. The first commercially available atomic force microscope was introduced in 1989. The AFM is one of the foremost tools for imaging, measuring, and manipulating matter at the nanoscale. The information is gathered by "feeling" the surface with a mechanical probe. Piezoelectric elements that facilitate tiny but accurate and precise movements on (electronic) command enable the very precise scanning. In some variations, electric potentials can also be scanned using conducting cantilevers. In newer more
advanced versions, currents can even be passed through the tip to probe the
electrical conductivity or transport of the underlying surface, but this is much more
challenging with very few groups reporting reliable data.

The AFM consists of a cantilever with a sharp tip (probe) at its end that is
used to scan the specimen surface. The cantilever is typically silicon or silicon
nitride with a tip radius of curvature on the order of nanometers. When the tip is
brought into proximity of a sample surface, forces between the tip and the sample
lead to a deflection of the cantilever according to Hooke's law. Depending on the
situation, forces that are measured in AFM include mechanical contact force, van
der Waals forces, capillary forces, chemical bonding, electrostatic forces, magnetic
forces, Casimir forces, solvation forces, etc. Along with force, additional quantities
may simultaneously be measured through the use of specialized types of probe.
Typically, the deflection is measured using a laser spot reflected from the top
surface of the cantilever into an array of photodiodes. Other methods that are used
include optical interferometry, capacitive sensing or piezoresistive AFM cantilevers.
These cantilevers are fabricated with piezoresistive elements that act as a strain
gauge. Using a Wheatstone bridge, strain in the AFM cantilever due to deflection
can be measured, but this method is not as sensitive as laser deflection or
interferometry.

If the tip is scanned at a constant height, a risk would exist that the tip
collides with the surface, causing damage. Hence, in most cases a feedback
mechanism is employed to adjust the tip-to-sample distance to maintain a constant
force between the tip and the sample. Traditionally, the sample is mounted on a
piezoelectric tube that can move the sample in the z direction for maintaining a
constant force, and the x and y directions for scanning the sample. Alternatively a
'tripod' configuration of three piezo crystals may be employed, with each responsible
for scanning in the x, y and z directions. This eliminates some of the distortion
effects seen with a tube scanner. In newer designs, the tip is mounted on a vertical piezo scanner while the sample is being scanned in X and Y using another piezo block. The resulting map of the area $s = f(x, y)$ represents the topography of the sample.

The AFM can be operated in a number of modes, depending on the application. In general, possible imaging modes are divided into static (also called contact) modes and a variety of dynamic (or non-contact) modes where the cantilever is vibrated.

![Figure 2.7: Photograph of Agilent’s PicoLE scanning probe microscope with options for AFM, MFM and SEM](image)

The Pico LE Scanning Probe Microscope from Agilent Technologies’ is a multi-functional system capable of contact/non-contact mode atomic force
microscopy, scanning tunneling microscopy and magnetic force microscopy. The multipurpose scanner used for analysis is an 8 micron scanner. Equipped with a very good software program for data collection, rendering and analysis the Pico LE is an ideal system for characterization of thin film samples. Typical tips used are silicon or silicon nitride tips depending on the necessary applications.

2.2.4 X-Ray Diffractometer with GIXRD and SAXS modes.

X-ray scattering techniques are a family of non-destructive analytical techniques which reveal information about the crystallographic structure, chemical composition, and physical properties of materials and thin films. These techniques are based on observing the scattered intensity of an X-ray beam hitting a sample as a function of incident and scattered angle, polarization, and wavelength or energy. X-ray diffraction finds the geometry or shape of a molecule using X-rays. X-ray diffraction techniques are based on the elastic scattering of X-rays. X-ray diffraction techniques are based on the elastic scattering of X-rays that have long range order. The most comprehensive description of scattering from crystals is given by the dynamical theory of diffraction. Powder diffraction is a technique used to characterize the crystallographic structure, crystallite size (grain size), and preferred orientation in polycrystalline or powdered solid samples. Powder diffraction is also a common method for determining strains in crystalline materials.

The Panalytical’s powder XRD system is a standard powder x-ray diffraction system capable of analyzing powder samples. Attached with a monochromator and accessories for grazing incidence x-ray diffraction the system is adept at analyzing thin film samples. Further, its SAXS modes feature allow us to study the particle size distribution in samples.
2.2.5 Vibrating Sample Magnetometer

A vibrating sample magnetometer is a scientific instrument that measures magnetic properties. A sample is placed inside a uniform magnetic field to magnetize the sample by physically vibrating the sample sinusoidally, typically by the use of a piezoelectric material. Commercial systems use linear attenuators of some form. Historically the development of these systems is done using modified
audio speakers, though this approach was dropped due to the interferences through the in phase magnetic noise produced. The induced voltage in the pickup coil is proportional to the sample's magnetic moment, but does not depend on the strength of the applied magnetic field. In a typical setup, the induced voltage is measured through the use of a lock-in amplifier using the piezoelectric signal as its reference signal. By measuring in the field of an external electromagnet, it is possible to obtain the hysteresis curve of a material.

2.2.6 Scanning Electron Microscope with Energy Dispersive Spectroscopy

The scanning electron microscope (SEM) is a type of electron microscope that images the sample surface by scanning it with a high-energy beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition and other properties such as electrical conductivity.

The types of signals produced by an SEM include secondary electrons; back scattered electrons (BSE), characteristic x-rays, light, specimen current and transmitted electrons. These types of signal all require specialized detectors that are not usually all present on a single machine. The signals result from interactions of the electron beam with atoms at or near the surface of the sample. In the most common or standard detection mode, secondary electron imaging or SEI, the SEM can produce very high-resolution images of a sample surface, revealing details about 1 to 5 nm in size. Due to the way these images are created, SEM micrographs have a very large depth of field yielding a characteristic three-dimensional appearance useful for understanding the surface structure of a sample.
The scanning electron microscope used for the work is the FEI’s Quanta 200 tungsten filament SEM. A typical electron microscope it is capable of resolving images up to a resolution of around 50nm. Attached with a dry EDS system the equipment is capable to elemental analysis of the samples in parallel with the imaging of the samples. Non conducting samples need to be typically coated with a catalyst before analysis.

2.2.7 Magneto Optic KERR Effect (MOKE)

When linearly polarized light reflects from a magnetic film, its polarization becomes elliptic (Kerr ellipticity) and the principal axis is rotated (Kerr rotation). The amount of rotation and ellipticity is proportional to a component of the
magnetization of the film. The type component measured depends on the optical configuration used. The most commonly used configurations are:

1. Perpendicular incidence. Here only the out-of-plane component of the magnetization is detected (polar Kerr effect).

2. 'Grazing' incidence (typically 30 degrees) using s-polarized light. This adds sensitivity to the component of M that lies in the film plane and in the plane of incidence (longitudinal Kerr effect). A considerable sensitivity to the out-of-plane component of the magnetization remains. Visible light only penetrates around 20 nanometer in typical metals. Therefore, with MOKE only the magnetization near the surface is probed. Since we are generally studying very thin films (typically tens of nm), this is not a real limitation.

![Figure 2.10](image.png)

**Figure 2.10**: Typical homemade Magneto Optic Kerr Effect (MOKE) setup.
2.2.8 Vibrating Sample Magnetometer (VSM)

A vibrating sample magnetometer is a scientific instrument that measures magnetic properties. A sample is placed inside a uniform magnetic field to magnetize the sample by physically vibrating the sample sinusoidally, typically by the use of a piezoelectric material. Commercial systems use linear attenuators of some form. Historically the development of these systems done using modified audio speakers, though this approach was dropped due to the interference through the in phase magnetic noise produced.

![Figure 2.11: Photograph of Lakeshore’s vibrating sample magnetometer system](image)

The induced voltage in the pickup coil is proportional to the sample's magnetic moment, but does not depend on the strength of the applied magnetic field.
In a typical setup, the induced voltage is measured through the use of a lock-in amplifier using the piezoelectric signal as its reference signal. By measuring in the field of an external electromagnet, it is possible to obtain the hysteresis curve of a material.

### 2.2.9 Four Point Probe measurement setup

![Figure 2.12: Schematic of four point probe setup.](image)

Four point probes method is an electrical impedance measuring technique that uses separate pairs of current-carrying and voltage-sensing electrodes to make accurate measurements than conventional two-terminal (2T) sensing. 4 terminal sensing is used in some impedance analyzers and ohmmeters, and in precision wiring configurations for strain gauges and resistance thermometers. 4-point probe is also an important tool used to measure sheet resistance of thin films. The main advantage of four-terminal sensing is that the separation of current and voltage electrodes eliminates the impedance contribution of the wiring and contact resistances.
Four-terminal sensing is also known as Kelvin sensing, after William Thomson, Lord Kelvin, who invented the Kelvin bridge in 1861 to measure very low resistances. Each two-wire connection can be called a Kelvin connection. A pair of contacts that is designed to connect a force-and-sense pair to a single terminal or lead simultaneously is called a Kelvin contact. A clip, often a crocodile clip that connects a force-and-sense pair when it closes or slides onto a conductor is called a Kelvin clip.