Chapter No. V

Electrodeposited Cadmium Chalcogenide Thin Films Studied by Double Exposure Holographic Interferometry Technique
5.1 Origin of Holography

Dennis Gabor was a German-trained electrical engineer, born in Budapest, Hungary, and interned in England during World War II. While there, he worked on a three-dimensional movie projection system in London, and later on electron microscope imaging for the British Thomson-Houston company in Rugby, England. The magnetic lenses of electron microscopes are imperfect for fundamental reasons - they distort the shape of the spherical electron waves coming from point-like objects. Gabor hoped to record that wave shape in the electron microscope, and then correct it with optical waves created by specially ground lenses, but to do this he had to be able to record wavefront shape as well as amplitude intensity, the wave’s phase or local direction in our terms. People had been struggling with this problem for years, and it was considered unsolvable until a key idea came to Gabor while he was waiting for a tennis court one Sunday afternoon. When Gabor published his two-beam recording method in 1948, it was dismissed by most “experts” until they took a close look at his example photographs - something obviously worked! But the requirements that the object and reference beam be coherent limited Gabor’s “holography” (inspired by the Greek for “whole” and “message,” holm and graphos) to very small objects. Gabor had not even thought about holography as a three-dimensional imaging technology until he saw the results at the University of Michigan in the early 1960s.

Emmett Leith and Juris Upatnieks were electrical engineers at the University of Michigan’s Willow Run Laboratories, near Ann Arbor. During the 1950s, they were working on a highly secret radar technique that allowed images of nearly photographic resolution to be generated by combining data from along a long flight path—the Project Michigan side-looking radar system. The key to the technique was an optical image-processing system that illuminated a long strip of radar data film with light from a mercury arc, focused it through a series of exotic lenses, and produced an incredibly detailed image. Slowly, Leith realized that he had rediscovered Gabor’s concepts of holography, but in a much more general
context. In 1962, low-power helium-neon lasers began to become commercially available, and Willow Run was one of the first labs to have one to experiment with. After verifying its usefulness for the side-looking radar project, Leith and Upatnieks started extending their ideas[10-13].

5.2 Introduction to Holography

Holography, is a technique employed to make three dimensional images. Holograms have a fascinating feature, parallax, which allows the viewer to observe the virtual object from different perspectives in full 3D, and a light wave interference pattern recorded on photographic film that can produce a three-dimensional image when illuminated properly. The term “holography” is a compound of the Greek words “holos = complete” and “grapho = to write.” It denotes a procedure for three-dimensional recording and displaying of images and information. Holography represents photographic process in a broad sense of this word, essentially differs from a usual photo because there is a registration not only intensity in a photosensitive material, but also phase of light waves, scattered by the object and carried the complete information about three-dimensional structure of the object. Therefore holography opens up completely new possibilities in science, engineering, graphics and arts, with image processing. Holographic optical elements and memories as well as art holograms[1-5].

Holography was invented in 1948 by Hungarian physicist Dennis Gabor (1900–1979), Nobel Laureate awarded the Physics in 1971. The first holograms that recorded 3D object were made in 1962 by Yuri Denisyuk in the Soviet Union and by Emmett Leith and Juris Upatnieks at University of Michigan, USA. Advances in photochemical processing techniques to produce high-quality display holograms were achieved by Nicholas J. Phillips[6-9].

5.3 History of Holography

The physical basics of holography are optics of waves, especially interference and diffraction. The first achievements are that of C. Huygens in 1629
to 1694, who phrased the following principle, every point that is hit by a wave is the origin of a spherical elementary wave. Using this statement a lot of problems of diffraction can be calculated by adding up the elementary waves. Important on the way of developing holography are also the works of T. Young in 1733 to 1829, A.J. Fresnel in 1788 to 1827 and J. von Fraunhofer in 1877 to 1926. Already at the beginning of the 19th century enough knowledge was at hand to understand the principles of holography. A lot of scientist were close to the invention of this method: G. Kirchhoff in 1824 to 1887, Lord Rayleigh in 1842 to 1919, E. Abbe in 1840 to 1905, G. Lippmann in 1845 to 1921, W.L. Bragg in 1890 to 1971, M. Wolfke and H. Boersch. But it took until 1948 when D. Gabor in 1900 to 1979) realized the basic ideas of holography.

Gabor made his first groundbreaking experiments using a mercury vapor lamp. At the beginning the holographic technique was of minor importance and was forgotten for some time. It was not until the coming up of laser technology when developments in holography experienced a significant upturn. In 1962 the theoretical aspects of this methods were refined by E. Leith and J. Upatnieks and a year later they showed off-axis holograms. This technique marks the breakthrough for the practical application of holography[14,15].

5.3.1 Photography and holography

To observe an object, it has to be illuminated properly. The light wave is characterized by two parameters the amplitude, which describes the brightness, and the phase, which contains the shape of the object. The objects have the same brightness but a different shape. For most holograms the color of the objects is not important, so the first chapters only deal with light waves of one wavelength. This changes for color holography which uses several wavelengths.
5.3.2 Photography

During the process of vision an object is imaged by the eye lens onto the retina. The optical path in a camera is similar: the objective creates an image on the film. For observation or to photograph an object it has to be illuminated. The scattered light, i.e., the object wave, carries the information of the object. The light wave can be made visible in a plane of the optical path, for example using a screen. In Fig. 5.1 the object wave appears as a very complex light field which results from the superposition of all waves emerging from the individual object points. If this light field could be recorded on a screen and displayed again, an observer (or a camera) would see an image that is not discriminable from the object [16,17].

![Figure 5.1 Principle of the imaging process by a lens (camera or eye).](image)

5.3.3 Holography

Holography allow the properties interference and diffraction of light which make it possible to reconstruct the object wave completely. Coherent laser light has to be used. “Coherence” means that the light wave is constant and contiguous. In Fig. 5.2 (a) the object and the reference waves interfere with each other on the holographic film. This generates interference fringes in the holographic layer. The information of the object wave is contained in the modulation of the brightness of the fringes and in the distance of the fringes[17].
Fig. 5.2 Principle of two stage imaging with holography (a) recording of a hologram and (b) reconstruction of the object wave.

5.4 Role of Interference and Diffraction during the recording and reconstruction process

5.4.1 Interference During Recording

A general description of the waves emerging from the object is complicated. Therefore for simplification a plane object wave is considered. The object in this case is a single point at a large distance. According to Fig. 5.3 (a), a plane object wave and a plane reference wave impinge on the photographic layer. The superposition of the waves creates equally spaced interference fringes, i.e., parallel bright and dark areas. Dark areas occur when the waves cancel out each other by superposition of a maximum and a minimum. Bright areas occur when maxima (or minima) of the waves are superimposed. After exposing and developing the photographic layer a grating is created where exposed areas appear dark.
Fig. 5.3 Hologram with a plane object wave: (a) recording of the hologram (fabrication of a diffraction grating) and (b) reconstruction of the object wave (diffraction by the grating).

5.4.2 Diffraction During Reconstruction

The image is displayed by illuminating the grating with a wave that closely resembles the reference wave Fig. 5.3 (b). According to Huygens’ principle each point of the grating sends out a spherical elementary wave. They are shown in Fig. 5.3 (b) for the center of the bright fringes. The superposition of the elementary waves can be shown by their envelope. Plane waves are created which represent the 0th, 1st, and -1st diffraction orders [1]. (Higher order of diffraction does not occur in sinusoidal gratings.) The zeroth order is the wave passing the grating in the direction of the impinging wave. The first order represents the object wave. Through the effect of diffraction the object wave is reconstructed; this is the principle of holography. The 1st order is often not desirable in this simple stage of holography, it is called the “conjugate object wave.”

5.5 Mathematical Approach

The principles of holography are contained in the simple Eq. (5.3) but the holographic process needs to be described more precisely. The following formulation relates to the most important method, the off-axis holography.

5.5.1 Holographic Recording and Reconstruction

The difference between photography and holography lies in the ability of holography to record the intensity as well as the phase of the object wave. If the amplitude and the phase of a wave are known in one (infinite) plane, the wave field is entirely defined in space.
(i) Recording

In Fig. 5.4.(a) the amplitudes of the object and the reference wave on the photographic layer are given by \( o \) and \( r \), respectively. These variables describe the intensity of the electromagnetic field of the light wave which impinges on the photosensitive layer. Both waves superpose, i.e., they form \( o + r \). In wave theory the intensity \( I \), the brightness, is calculated as the square of the amplitude:

\[
I = |r + o|^2 = (r + o)(r + o)^* \quad \text{(5.1)}
\]

The bold letters represent complex functions which are During the recording of the hologram. Equation (5.1) can be written as

\[
I = |r|^2 + |o|^2 = r^* o + r o^* \quad \text{(5.2)}
\]

Where, the \( r^* \) represents the complex conjugate. Especially the last term containing the object wave \( o \) is important for holography. The darkening of the holographic film is dependent on the intensity \( I \). Thus the information about the object wave \( o \) is stored in the photographic layer.

(ii) Reconstruction

The recording process of the object wave will be a lot more understandable after dealing with the following calculations for the image reconstruction. The reconstruction is performed by illuminating the hologram with the reference wave Fig.5.4(b), For simplification we will assume that the amplitude transmission of the film material is proportional to \( I \) which is contrary to usual film processing. (Strictly speaking this assumption is of no relevance, since the effect of the diffraction pattern is the same when exchanging bright and dark fringes.) Therefore the reconstruction yields the light amplitude \( u \) directly behind the hologram:

\[
u \sim r \cdot I = r(|o|^2 + |r|^2) + r o^* \quad \text{(5.3)}
\]

\[
= u_0 + u_{-1} + u_{+1}
\]
Fig. 5.4 Description of holography (off-axis hologram) (a) recording (b) reconstruction

The wave field behind the hologram is composed of three parts. The first term $u_0$ governs the reference wave which is weakened by the darkening of the hologram by a factor of $(|o|^2 + |r|^2)$ (zeroth diffraction order). The second term $u_{-1}$ essentially describes the conjugate complex object wave $o^*$. This corresponds to the $1^{\text{st}}$ diffraction order. In the last term $u_{+1}$ the object wave itself is reconstructed with the amplitude of the reference wave $|r|^2$ being constant over the whole hologram. This proves that the object wave $o$ can be completely reconstructed. It represents the first diffraction order[18,19].

5.5.2 Importance of object and reference Wave

The complex amplitude of the object wave $o(x, y)$ is a complicated function; the absolute value $|o(x, y)|$ and phase $\Phi(x, y)$ are dependent on the coordinates $x$ and $y$ on the photographic plate. In the following only the amplitudes in the hologram plane are described; this is sufficient to describe the whole wave field as long as the hologram is large enough. If the time dependence of the waves is not considered, Eq. (5.3) for the object wave can be written as
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\[ o(x, y) = lo(x, y)e^{-i\phi} = o(x, y)e^{-i\phi}. \]  (5.4)

Complex functions are written in bold letters while the same letters in normal font are used for their absolute value. Usually the reference wave \( r(x, y) \) is a plane wave. The absolute value \( r \) remains constant for uniform illumination. Shown in Fig. 5.5, the phase \( \Psi \) depends on the angle of incidence \( \delta \) and can be calculated by

\[ r(x, y) = re^{-i\Psi} = re^{(2\pi\sigma r x)} \]  (5.5)

The distance of two maxima of the reference wave in the hologram plane is given by

\[ dr = \frac{1}{\sigma r} = \frac{\lambda}{\sin \delta} \]  (5.6)

Where, \( \sigma r \) is the so-called spatial frequency of the wave, i.e., the number of maxima per length unit.

5.5.3 Recording

The intensity in the plane of the photographic layer is therefore given by from Eq. (5.2)

\[ I = |r(x, y) + o(x, y)|^2 = |r(x, y)|^2 + |o(x, y)|^2 + r^* (x, y)o(x, y) + r(x, y)o^* (x, y) \]  (5.7)

Fig. 5.5 Phase \( \psi = -2\pi \Delta/\lambda \) of an angular incident wave on a hologram

The four summands can be calculated as

\[ |r(x, y)|^2 = r^2 \]
\[ |o(x, y)|^2 = o^2 \]
\[ r^2(x, y)o(x, y) = ro(x, y) e^{-2i\sigma r x} e^{-i\Phi(x, y)} \]
\[ r(x, y)o^*(x, y) = ro(x, y) e^{2i\sigma r x} e^{i\Phi(x, y)} \] (5.8)

Using the Euler formula \( e^{\varphi} + e^{-\varphi} = 2 \cos \varphi \) this can be written as
\[ I(x, y) = r^2 + o^2(x, y) + 2ro(x, y) \cos[2\pi\sigma r x + \Phi(x, y)] \] (5.9)

The equation shows that the intensity distribution in the photographic layer contains the object wave’s amplitude \( o(x, y) \) as well as the phase \( \Phi(x, y) \). The amplitude \( o(x, y) \) modulates the brightness while the phase modulates the distance of the fringes with a spatial carrier frequency \( \sigma_r (= \text{fringes / length unit}) \).

The transmission decreases proportional to the exposure intensity \( I \) and the exposure time \( \tau \). The transmission without any exposure is given by \( t_0 \):
\[ t = t_0 + \beta \tau I = t_0 + \beta E. \] (5.10)

The term \( E = \text{I} \tau \) describes the energy density of the light, commonly called the “exposure.” The parameter \( \beta \) is negative and is represented by the slope in the H and D curve. The amplitude transmission is then given by
\[ t(x, y) = t_0 + \beta \tau r^2 + \beta \tau o^2(x, y) + \beta \tau ro(x, y) e^{-i2\pi\sigma r x} e^{-i\Phi(x, y)} + \beta \tau ro(x, y) e^{i2\pi\sigma r x} e^{i\Phi(x, y)}. \] (5.11)

The transmission \( t \) of a plane object wave \( o \) which illuminates the photographic layer similar to the reference wave in Eq. (5.5) can be easily calculated:
\[ o = e^{i2\sigma o x}. \]

Combining Eq. (5.11) with \( \Phi = -2\pi\sigma o x \) and the Euler equation then gives
\[ t(x) = t + t_1 \cos (kx) \] (5.12)
\[ k = 2\pi (\sigma_r + \sigma_o) \]
\[ t = t_0 + \beta \tau (r^2 + o^2(x, y)) \]
\[ t_1 = \beta \tau ro \]

The amplitude transmission \( t \) of a hologram formed by two planewaves \( r \) and \( o \) is therefore a cosine-like diffraction grating. Hence the intensity transmission \( T = t^2 \) is proportional to a \( \cos^2 \) function.
5.5.4 Reconstruction

For the reconstruction of the object wave the developed hologram is again illuminated with the reference wave \( r(x, y) = rei2\pi\sigma r x \). The hologram \( t(x, y) \) acts like a filter and the wave field \( u(x, y) \) directly behind the photographic layer is given by

\[
\begin{align*}
    u(x, y) &= r(x, y) t(x, y) \\
    &= (t_0 + \beta r^2) r(x, y) + \beta r o^2(x, y) r(x, y) : u_0 + \\
    &\quad \beta r^2 o(x, y) : u_{+1} + \beta r^2 o^*(x, y) e^{i4\pi\sigma r x} : u_{-1}
\end{align*}
\] (5.13)

With Eqs. (5.5), (5.6), and (5.11) this becomes

\[
\begin{align*}
    u(x, y) &= (t_0 + \beta r^2) r(x, y) + \beta r o^2(x, y) r(x, y) : u_0 + \\
    &\quad \beta r^2 o(x, y) : u_{+1} + \beta r^2 o^*(x, y) e^{i4\pi\sigma r x} : u_{-1}
\end{align*}
\] (5.14)

This expression describes the effect of a hologram on a light wave during the reconstruction. It is given by four summands which are written in four lines (see also Fig. 5.4(b).

The first summand refers to the intensity reduction of the reconstruction wave (=reference wave) by the factor \( t_0 + \beta r^2 \) during reconstruction. The second term is small assuming that we choose \( o(x, y) < r \) during recording. This term is distinguished from the first term by its spatial variation \( o^2(x, y) \). The \( o^2(x, y) \) term contains low spatial frequencies which have small diffraction angles and create a so called halo around the reconstruction wave[20-25].

5.6 Basic Imaging Techniques in Holography

The recording of a hologram is performed by bringing object and reference wave to interference. The superposition of an object wave of a point O with a reference wave is shown in Fig. 5.6. In Fig. 5.6 (a) the reference wave emanates as a spherical wave from the point source R; in contrast Fig. 5.6 (b) shows a plane wave as a reference wave, i.e., point R is shifted leftward to infinity. Different holographic methods result depending on the position of the holographic layer within the interference field during the recording:

1. In-line hologram after Gabor (Fig. 5.6, position 1)
2. Off-axis hologram after Leith and Upatnieks (positions 2, 2\(^1\), 2\(^{11}\))
3. Fourier hologram (position 3)
4. Fraunhofer hologram (position 4)

5. Reflection hologram after Denisyuk (positions 5, 51) & etc.

5.6.1 In-Line Hologram (Gabor)

The technique of straightforward holography developed by Gabor places the light source and the object on an axis perpendicular to the holographic layer. Holography as shown at position 1 in Figs. 5.6 (a) and (b). Only transparent objects can be considered. The object wave is represented by the part of the light diffracted by the object whilst the undiffracted part serves as the reference wave (Fig. 5.6 (a). In principle, both plane and spherical reference waves can be used.

If an axial point O is chosen as an object emitting a spherical wave the resulting hologram for a plane reference wave is a Fresnel zone lens. (Using spherical reference waves results in similar Fresnel lenses.)

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Fig. 5.6 Interference fringes during the recording of holograms of an object point O. 1 In-line hologram after Gabor (thin); 2, 21 Off-axis hologram after Leith–Upatnieks (thin); 211 Off-axis hologram (thick); 3 Fourier hologram (lensless);
4 Fraunhofer hologram; 5 Reflection hologram after Denisyuk (thick); 5\textsuperscript{1} Reflection hologram.

Disadvantage of in-line or straightforward holograms is obvious: during reconstruction the hologram is illuminated with a plane reference wave according to Fig. 5.6. (b). Since it represents a zone lens a virtual image point is formed at the original point and additionally a real image point appears at the same distance to the right of the hologram. The phenomenon also holds for extended objects which can be divided into single points. During observation the two images lying on the same axis interfere which leads to image disturbances Fig. 5.6. (b). Moreover, the observer looks directly into the reconstruction wave. Because of these disadvantages this form of holography is only of historical interest. A single laser beam is used for the recording which constitutes the object and reference wave without splitting the beam. Such techniques are called “single beam” holography. The hologram is illuminated from the backside when observing the image; it is called a “transmission hologram.” From Fig. 5.6, it is apparent that the interference lines are perpendicular to the light sensitive layer and have a relatively large distance. For common film layers the hologram can be classified as “thin” particularly since the grating spacing is relatively large. The difference between the so called “thin” and “thick” holograms will be explained in types of holograms.
Fig. 5.7 In-line holography for transparent objects (Fig. 5.6, position 1): (a) recording of the hologram and (b) reconstruction of the hologram.

In Fig. 5.4. The coherent light source as well as the object, which is a transparency containing all the small details on a clear background, located along axis normal to photographic plate. When the object is illuminated with a uniform parallel beam gives two parts, the first is a relatively strong, uniform plane wave to the directly transmitted light. This constitutes the reference wave and since its amplitude and phase do not vary across the photographic plate, its complex amplitude can be written as a real constant ‘r’. The second is a weak scattered wave due to the transmission variation in the object[23,24].

The complex amplitude of this wave, which varies across the photographic plate, can be written as \( O(x, y) \),

\[
|O(x, y)| << r
\]

(5.12)

where, the resultant complex amplitude at any point on the photographic plate is the sum of these two.

The intensity at this point is,

\[
I(x, y) = |r + O(x, y)|^2
= r^2 + |O(x, y)|^2 + rO(x, y) + rO'(x, y)
\]

(5.13)

A positive transparency is made from this recording. It is assumed that its amplitude transmittance ‘t’ is the ratio of the transmitted amplitude to that incident on it. Therefore,
\[ t = t_0 + \beta TI \]  
(5.14)

Where, 
- \( t_0 \) - background transmittance
- \( T \) - exposure time
- \( I \) - intensity
- \( \beta \) - parameter determined by the photographic material used and the processing conditions.

The amplitude transmittance is,
\[ r(x, y) = t_o + \beta T \left[ r^2 + |O(x, y)| + rO(x, y) + rO^*(x, y) \right] \]

For reconstruction of image this transparency is placed in the same position as the original photographic plate[26,27].

So the complex amplitude transmission by the hologram is,
\[ u(x, y) = r(x, y) \]
\[ = r(t_0 + \beta Tr_o o(x, y) + \beta Tr^2 o'(x, y)) \]  
(5.15)

Where,
\[ r(t_0 + \beta Tr^2) \] represents uniformly attenuated plane wave. The second term \( \beta Tr|O(x, y)|^2 \) being extremely small can be neglected and \( \beta Tr|O'(x, y)|^2 \) is a constant factor, the same as the original wavefront from the object incident on the photographic plate. It should be noted that the hologram used to reconstruct the image must be a positive transparency [21].

**5.6.2 Off-Axis Hologram (Leith–Upatnieks)**

It turns out to be more favorable to shift either the holographic layer or the object sideways and use position 2 or 2\(^1\) according to Fig. 5.6. This technique was developed by Leith and Upatnieks and has prevailed for many applications. Laser beam, object, and hologram are not on the same axis anymore.

The hologram represents the outer area of a fresnel zone lens (at least in setup 2\(^1\)). Again a virtual and a real image are formed during reconstruction. For
position 2\(^1\) of the hologram both images lie at the same position as with Gabor holography (position 1). The advantage of off-axis holography is that both images are positioned at different angles regarding hologram 2\(^1\). Therefore the images do not interfere during observation and image disturbances are avoided. The setup for off-axis holography is in Fig. 5.8. By tilting the reference wave (or shifting the object) it is achieved that the three diffraction orders, namely the image, the conjugated image, and the illumination wave, are spatially separated. This has the advantage that also holograms of opaque objects can be produced since the reference wave is not obstructed by the object.

The setups according to Figs. 5.7 and 5.8 generate transmission holograms. The formation of a “thin” or “thick” grating depends on the thickness of the holographic layer, the grating spacing and the direction of the grating planes. In practice, mostly thin transmission holograms occur. They can only be reconstructed with monochromatic light since every color generates a different diffraction angle for the image position. The use of white light generates a totally blurred image due to these chromatic aberrations. In thick transmission holograms Bragg reflection only occurs for the wavelength used during recording. This makes it possible to use white light for reconstruction. The effect gets stronger with increasing tilt angle of the grating planes. With 45\(^0\) tilt the reconstruction can be done with almost white light. Although this means grazing incidence for the reconstruction wave, for the conjugated image the Bragg condition is not satisfied and it does not appear. The diffraction efficiency of the virtual image is therefore increased. If the photographic layer is placed at position 2\(^1\) Fig. 5.6, a thick hologram is formed more likely than in positions 2 and 2\(^1\) since the grating lines are closer together.

\[
O(x, y) = |O(x, y)| \exp[i\phi(x, y)]
\]

In Fig. 5.6, it is not obvious whether off-axis holograms are produced using a single beam or a multiple beam technique. In principle, both are possible. In
split-beam holography the reference wave is separated from the illumination of the object by a beam splitter.

\[ r(x, y) = r \exp(i2\mu x) \]

While due to the reference beam is

The complex amplitude due to the object beam at any point \((x, y)\) on the photographic plate is

\[ u(x, y) = r(x, y) t(x, y) \]

where,

\[ t(x, y) = t_o + \beta T \left[ O(x, y)^2 \right] + r |O(x, y)| \exp[-i\phi(x, y)] \exp(-2i\Pi r x) + r |O(x, y)| \exp(2i\Pi r x) \]
5.7 Essential requirements for recording of holograms

5.7.1 Coherence

With coherent light interference effects can be observed, i.e., constructive and destructive superposition of the field amplitudes of light waves. On the other hand, no interferences appear for incoherent light; the intensities superpose additively and the creation of a hologram is not possible. For partially coherent light the contrast of the interference effects is decreased.

5.7.2 Spatial Coherence

It is distinguished between spatial and temporal coherence. The spatial coherence describes the correlation of field strengths or amplitudes in two different points of a wave field at a given point in time. The investigation of the coherence can be done with an interference experiment using two pinholes in the wave field (Fig. 5.9). Complete coherence creates interference fringes that are modulated down to zero if the two amplitudes are the same. For partial coherence the contrast is decreased. A laser oscillating in a single transversal mode, e.g., TEM$_{00}$, is completely spatially coherent. A transversal multimode laser has a low spatial coherence because the transversal modes have different frequencies and therefore temporal varying phase differences. In holography mostly TEM$_{00}$ lasers are used so that the radiation is spatially coherent.

![Fig. 5.9 Principle of measuring spatial coherence.](image)

Fig. 5.9 Principle of measuring spatial coherence.
5.7.3 Temporal Coherence

In contrast to their spatial coherence lasers used for holography are not ideal temporal coherent. For temporal coherence the field strengths or amplitudes of a light wave are compared or “correlated” at a fixed point in space but for different points in time. In general, it can be observed that the field strengths for two different points in time have a constant phase difference. But if the spatial difference exceeds a specific maximum value, the so-called “coherence time tc,” the phase difference varies statistically. The coherence time can be measured experimentally with a Michelson interferometer. The retardation can be chosen so large that no interference occurs anymore. Therefore coherence length and coherence time are measurable.

The coherence length is defined as the distance after which the contrast of the interference fringes has decreased to $(1/e) = 37\%$. For conventional light sources the emission consists of single spontaneously emitted photons or wave packets with a duration $\tau$ which corresponds to the lifetime of the emitting energy level. From one wave packet to the other the phase varies statistically so that the following coherence time results:

$$tc \approx \tau.$$  \hspace{1cm} (5.16)

The duration of a wave packet and the lifetime $\tau$ are connected to the spectral width $\Delta f$ of the wave by the following equation:

$$tc \approx \frac{1}{\Delta f}.$$  \hspace{1cm} (5.17)

Although lasers do not emit wave packets, but a wave with constant amplitude, Eq. (5.17) can also be applied to lasers. Thus the coherence length is limited by the bandwidth of the laser radiation.

The distance traveled by the light in the time $tc$ is called “coherence length:”

$$lc = Ctc = \frac{C}{\Delta f}.$$  \hspace{1cm} (5.18)

Where, $c$ denotes the speed of light.
5.7.4 Coherence Length

For long lasers according to Fig. 5.10 always several modes appear [60]. The number \( N \) can be easily estimated by dividing the whole line width \( 2\Delta f_l \) by the distance of the modes \( c/2L \):

\[
N \approx \frac{2\Delta f_l}{c/2L} \quad \text{(5.19)}
\]

The coherence length is calculated according to Eqs. (5.18) and (5.19) to

\[
l_c = \frac{2L}{N} . \quad \text{(5.20)}
\]

Fig. 5.10 Michelson Interferometer

It increases with the resonator length \( L \) and decreases with the number \( N \) of longitudinal modes. Eq. (5.20) is not valid for \( N = 1 \) since the width of a single mode has to be used for the bandwidth in Eq. (5.18)

5.8 Vibration Isolation

The optical setup has to be mechanically so stable during the holographic recording that the movement of the interference fringes is small compared to the light wavelength. In this case mechanical vibrations of the building can cause blurring of the interference fringes in the hologram plane. Therefore it is necessary to use vibration isolating tables when working with continuous lasers. The isolation of the vibrations has to be dimensioned in a way that the amplitudes in the holographic setup are maximal in the nm region[31-35]. Causes of vibration
can be running machines, air conditioners, traffic, or moving persons. There are various designs for vibration isolation tables. In our system a heavy concrete slab rested on air support as shown in Fig.5.11.

A vibration isolating table usually consists of two parts which both play an important role for the isolation:

**Isolators:** The tabletop is placed onto vibration isolators which can be constructed in several ways. They decrease the transfer of vibrations to the optical setup.

**Table top:** The construction of the table top can be chosen such that further absorption of vibrations is achieved. This holds especially for metal tops with honeycomb structures. More simple tops are made of natural or artificial stone. The isolators have to be adjusted to the mass of the table top. Fig.5.12 shows the photograph of vibration isolation table.

![Fig.5.11 Vibration isolation Table](image)

5.9 Holographic recording media

The recording medium must be able to resolve the interference fringes. It must also be sufficiently sensitive to record the fringe pattern in a time period short enough for the system to remain optically stable, i.e. any relative movement of the two beams must be significantly less than \( \lambda/2 \).

The recording medium has to convert the interference pattern into an optical element which modifies either the amplitude or the phase of a light beam which is incident upon it. These are known as amplitude and phase holograms respectively. In amplitude holograms the modulation is in the varying absorption of the light by the hologram, as in a developed photographic emulsion which is less or more absorptive depending on the intensity of the light which illuminated it. In phase holograms, the optical distance (i.e., the refractive index or in some cases the thickness) in the material is modulated.

5.9.1 Recording materials

Recording material for holography should have a spectral sensitivity well matched to available laser wavelengths, a linear transfer characteristic, high resolution and low noise.

Silver halide

Recording material for holography, silver halide photographic emulsions are the most widely used, mainly because of their relatively high sensitivity and
because they are commercially available. In addition, they can be dye sensitized so that their spectral sensitivity matches the most commonly used laser wavelengths [36].

Silver halide photographic emulsion was used by Gabor to form the first holograms, because it has relatively high sensitivity and can be readily purchased; it remains the most common recording material. However, the emulsion, which is widely used, was not originally intended for laser light recording. Recently Agfa-Gevaert Inc. has made available silver halide emulsion specially sensitized for laser light photography and holography. When a two beam interference pattern exposes a photographic plate and is developed, an absorption hologram is formed. During the development process the exposed silver halide grains are converted to metallic silver. A bleach process may be used after development to convert the silver into a transparent compound; this in turn converts the absorption hologram to a phase hologram. Both transmission and reflection holograms can be recorded in photographic emulsion. The silver halide grains found in emulsions suitable for holography are typically less than 0.1µm in diameter.

In addition to this, many recording materials are available. e.g. Dichromated gelatin, Photoresists, Photopolymers etc [37,38].

5.9.2 The developing process in holography

Developing process by which, the latent image recorded during the exposure of the material is converted into a silver image. In chemical development, this processing technique is called chemical reduction. From the chemical point of view, reduction is a process in which oxygen is removed from the chemical reducer, and reduction is always accompanied by a reciprocal process called oxidation.

Silver chloride, bromide and iodide are collectively known as silver halides. For fine seen of the fringes, the photographic emulsion of photographic plate needs to have very high resolution and excellent emulsions. In the manufacture of a photographic emulsion the silver halide is compressed as dispersion of
exceedingly small particles in gelatin. When coated on a glass or film base and allowed to dry; this becomes a thin, tough, transparent layer which is very sensitive to short wavelength of light. When light is allowed to fall on the emulsion its energy is absorbed by silver halide particles, causing local disruptions of some bonds that hold the crystalline structure together and release free silver atoms within the body of the crystal. The developer is used to turn the latent image into a visible photographic image in metallic silver, a process called reduction. This solution containing a reducing agent is capable of reducing silver halide to silver, but only in the case of those crystals which bear a latent image.

1. Developing and Fixing Process

Silver halide materials used for holography are all of the fine grained type. Most of the commercially available photographic films and plates consist of silver halide emulsion coated on a transparent glass substrate. Therefore, a great deal of research has been done into the problem of processing methods of holographic silver halide emulsions.

Kodak D-19 developer is the most frequently used conventional developer for holograms[39].

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metol</td>
<td>2.2 gms.</td>
</tr>
<tr>
<td>Sodium Sulphite</td>
<td>7.2 gms.</td>
</tr>
<tr>
<td>Hydroquinone</td>
<td>8.8 gms.</td>
</tr>
<tr>
<td>Sodium carbonates</td>
<td>48 gms.</td>
</tr>
<tr>
<td>Potassium bromide</td>
<td>4 gms.</td>
</tr>
<tr>
<td>Distilled water</td>
<td>1000 ml</td>
</tr>
</tbody>
</table>

The photographic plate rinsed in developer for about three minutes. After development, the photographic plate is just dipped in water to avoid mixing of developer and fixer. The plate is then kept in fixer solution for about five minutes. Generally, sodium-thio-Sulphate is used as a fixer. The processed plate is washed in flowing water for about four minutes.
2. Bleaching of holographic films

Bleaching is a particularly important technique for holograms recorded on holographic materials since it constitutes the only way of producing holograms with high diffraction efficiency on these materials. When a holographic emulsion is developed, all crystals of silver halide which bear a latent image are converted into opaque grains of silver which replicate the pattern formed by the interference of the object and reference beam. If we can turn the silver into a transparent substance of high refractive index, no light will be absorbed. All the light will be used to form the holographic image and we will get a considerable improvement in diffraction efficiency [40,41].

One method of bleaching consists of treating the hologram with an acidic dichromatic solution. Greater irradiance on any small region gives more silver after normal processing and thicker or larger dichromate on the area after bleaching.

5.10 Holographic Interferometry

The holographic interferometry is used in technology to measure small deformations of objects. The advantage compared to photoe-lasticity is that small deformations (<1 µm) of diffuse reflecting objects can be measured. This way, the holographic interferometry plays an important role in the nondestructive material testing. Static and dynamic holographic methods are used in the automotive industry to measure stress and strain, deformations and vibrations qualitative and quantitative. For a more in-depth understanding of the quantitative analysis as well as digital methods the reader is referred to the literature [42-44].

5.10.1 Real-Time Interferometry

Much larger flexibility for the observation of interference effects is offered by real-time interferometry. The interferometric phenomena can be seen while they are evolving and the effects of changes made to the experimental setup when testing an object can be observed immediately.
The illuminated object is viewed through a hologram which was made from the undisturbed object before the experiment and that is replaced to its original position during the recording. Consequently, our eye is hit by the reconstructed object wave \( o \) as well as the scattered object wave \( o' \). Figure 5.13 shows the imagined path of the object waves \( o \) and \( o' \) to the right of the hologram. The difference is exaggerated here. On the left side only the object wave \( o' \) exists, i.e., the scattered light from the deformed object[45,46].

![Hologram Diagram](image)

Fig. 5.13 Real-time holography. The undisturbed object wave \( o \) is read out from the hologram by the reconstruction wave \( r \). It is then superposed by the object wave ‘\( o' \) which is scattered from the deformed object directly.

### 5.10.2 Time Average Interferometry

The time average interferometry is used to measure the oscillation amplitude of an object oscillating with a frequency of \( f = \frac{\omega}{2\pi} \). Here the exposure time is much larger than the oscillation period \( 2\pi/\omega \). The displacement vector can be written as

\[
d = d(r) \sin(\omega t) \tag{5.21}
\]

For simplification we assume an oscillation in the \( z \)-direction, which is shown in Fig. 5.14 for the two-dimensional case. For harmonic oscillations applies:
Fig. 5.14 Time average interferometry in a two dimensional example. A sinusoidal oscillation causes a periodic displacement of the object point P into the new position P'. S = sensitivity vector, d = displacement vector

\[ d = d(z) \sin(\omega t). \quad (5.22) \]

The according phase shift \( \delta \) is,

\[ \delta = Sd \sin(\omega t). \quad (5.23) \]

For the complex amplitude of the object wave this results in,

\[ o(z, t) = o(z) e^{i(-\Phi + Sd \sin(\omega t))} \quad (5.24) \]

The reconstructed wave \( u(z) \) is the time average of many individual waves registered during the exposure time \( \tau \) according to Eq. (5.24),

\[ u(z) = \frac{1}{T} \int_{0}^{T} o(z, T) dt \quad \text{or} \]

\[ u(z) = o(z)e^{-\Phi} \frac{1}{T} \int_{0}^{T} e^{iSd \sin(\omega t)} dt \quad (5.25) \]

The following expression,

\[ M = \frac{1}{T} \int_{0}^{T} e^{iSd \sin(\omega t)} dt \quad (5.26) \]

is called the “characteristic function” or “modulation function.” The integral can be expanded into a power series of Bessel functions. Since the exposure time is very long only the Bessel function \( J_0 \) adds to the integral:

\[ M = J_0 (Sd). \quad (5.27) \]
For Eq. (5.25) follows,

\[ u(z) = o(z)e^{-i\Phi}Jo(Sd) \]

The observed intensity \( I \propto |u|^2 \) is then,

\[ I(z) = IoJ_0^2(Sd) \] (5.28)

The slope of \( J_0^2 \), the intensity maxima decrease very quickly with increasing order \( N \).

The determination of \( \delta (=Sd) \) from the order \( N \) is a little bit more complicated than for the interference techniques mentioned before because although \( J_0^2 \) is an oscillating function it is not periodic. If the fringe order is not an integer or half-integer number the needed interpolation methods get quite complicated. However, positions of zeroth order, i.e., nodal points, can be found very easy with this method since they are reconstructed with full intensity \( (J_0^2 = 1) \) [47-49].

### 5.10.3 Sandwich Method

In the past Abramson proposed the sandwich method in order to overcome these problems for not too complicated objects. The essential part is that not only both recordings of the double exposure are performed after each other as mentioned above but that they are done on different plates at the same place. To evaluate the interference effect both plates are reconstructed as a sandwich.

Since it is not possible to have both plates at the same place during the later reconstruction from the beginning two plates are exposed as a sandwich for each recording, with and without deformation. That way it is made sure that during the reconstruction of two plates from two different recordings the geometry and the path of light are still the same for both recording situations. The procedure is rather complicated and therefore it is not applied very often. The advantage of the sandwich method is that the direction of the deformation can be determined by tilting the sandwich until the interference fringes vanish [33].
5.10.4 Double-Exposure Interferometry

In a double-exposure holographic interferometry, two images of the same object are stored in one photographic layer. A first one in undisturbed state and a second with a slightly deformed object. During the reconstruction both object waves are “read out” and they interfere with each other. This creates clearly visible interference fringes which cover the whole object. The distance of two bright fringes correspond to a phase shift of \(2\pi\) or \(\lambda\), respectively. The density of the fringes shows the spatial distribution of the deformation. For very large deformations of more than 100 µm then the distance of the fringes becomes so small that an evaluation is almost impossible. The lower limit of recognizable disturbances is fractions of a wavelength, i.e., when using He–Ne lasers well below 0.1 µm[50-53].

5.11 Application of Double Exposure holographic interferometry

5.11.1 Non destructive testing with Holographic interferometry

Non destructive testing is used to determine whether or not a component has a fault without causing material damage the process of the test. HI techniques are suitable for this application since they are non-contacting and can detect surface displacements that results form the application of small loads. The defect such as cracks, voids, debonds, declaminations, imperfect fits, interior irregularities, inclusions could be seen with NDT. It is a viable tool for engineering design, inspection, quality control and testing etc.

The technique of HI is very efficiently used for large number of industrial applications, as well as for biological and medical studies with the help of non destructive testing [54-56].

5.11.2 Other applications with limitation

Holographic interferometry has used for measuring microscopic deformation and electrochemical techniques for determining the corrosion current of metallic samples. The study on the effect of cyclic deformations on the
corrosion behavior of polarized metallic electrodes in aqueous solution was conducted by using the HI technique.

Studied the phase shifting double-exposure interferometry with fast photo refractive crystals and by this technique studied quasi real-time holographic interferometry with reflection type objects. It is based on fast sequence of holographic double exposure interferograms recorded in sillenite-type photorefractive BTO crystals[57].

Applied DEHI to study the new formulas allow an accurate theoretical description of reflection gratings in sillenites. Holographic recording in reflection geometry offers high lateral image resolution and a compact and simple setup. They combine this resolution three-dimensional imaging with holographic double exposure interferometry to allow the analysis of a dynamic process on the microscopic scale.

**Advantages of DEHI**

1. DEHI is much easier than real-time HI, because the two interfering waves are always reconstructed in exact register.
2. Distortions of the emulsion affect both images equally, and no special care need be taken in illuminating the hologram when viewing the image.
3. In addition, since the two diffracted wavefronts are similarly polarized and have almost the same amplitude, the fringes have very good visibility.

**Limitations of DEHI**

The object has not moved between the exposures, the reconstructed waves, both of which have experienced the same phase shift, add to give a bright image of the object. This makes it difficult to observe small displacements. A dark field, which gives much higher sensitivity, can be obtained by holographic subtractions.

**5.12 Recording of hologram by double exposure holographic interferometry.**

The experimental setup for recording hologram of the thin films is as shown in Fig.5.12,
Fig. 5.12 Experimental setup for recording hologram of the thin films

Fig. 5.13, 5.14 and 5.15 shows the recording holograms of CdS films developed on the holographic film. From the hologram study, it is observed that the time of deposition increases, the number of fringes localized on the surface of stainless steel substrate increases and consequently the fringe width decreases. While recording the hologram, the object was illuminated with a beam of light making an angle of $\theta_1$ with the normal and viewed at an angle $\theta_2$ during reconstruction. The reconstructed image has a superimposed fringe pattern corresponding to displacement of the surface [58,59].

The displacement $d$ of the surface, in normal direction is given by

$$d = \frac{n\lambda}{\cos\theta_1 + \cos\theta_2}$$

(5.29)

where, $n$ is the number of fringes and

$\lambda$ is the wavelength of light used.

In general, the angles $\theta_1$ and $\theta_2$ are sufficiently small so that,

$$d = \frac{n\lambda}{2},$$

(5.30)

After counting the relevant number of fringes, one can quantitatively determine the displacement of a point on the surface of object i.e., deformation of the object surface was determined. Thus, using Eq. (5.30), the thickness of the films is
calculated and listed in Table 5.1.

The mass of the film is calculated using the relation,

$$\text{Mass} = \text{density} \times \text{volume}$$  \hspace{1cm} (5.31)

The stress to substrate is given by the following formula [60,61]

$$S = \frac{\tilde{S}}{3l^2d}$$ \hspace{1cm} (5.32)

where,

$$\tilde{S} = \text{Stress in dyne/cm}^2,$$

$$t_s = \text{is the substrate thickness},$$

$$\Delta = \text{is the deflection of the substrate equal to } 4\lambda/2, l \text{ is the length of the}$$

substrate on which thin film is deposited and

$$Y_s = \text{is the Young’s modulus of the substrate}.$$

The thickness and stress are determined by using the Eq. (5.32) and tabulated in Table 5.1. The Variation of mass of CdS films deposited on stainless steel substrate, stress to the substrate and fringe width, against the deposition time is as shown in Fig. 5.16, 5.17 and 5.18.

5.13 Surface deformation study of CdS thin films

The Double Exposure Holographic Interferometry (DEHI) technique is used to determine, thickness of thin film, mass deposited on stainless steel substrate and stress to substrate of electrodeposited CdS, CdSe and CdTe thin films for various deposition time and at various concentrations.

Here, the Double Exposure Holographic Interferometry (DEHI) technique is used to study the surface deformation on stainless steel substrate, when CdS, CdSe and CdTe is deposited on it.

5.13.1 Preparation

To deposit CdS thin films onto the stainless steel substrate, for bath concentration ($A_2$) = 0.04 M CdSO$_4$ + 0.4 M Na$_2$S$_2$O$_3$ + 0.06 M EDTA, ($B_2$) = 0.06 M CdSO$_4$ + 0.6 M Na$_2$S$_2$O$_3$ + 0.08 M EDTA and ($C_2$) = 0.08 M CdSO$_4$ + 0.8 M Na$_2$S$_2$O$_3$ + 0.1 M EDTA. for different deposition time, (i) 110 sec. (ii) 120 sec.
(iii) 130 sec. solutions of AR grade CdSO₄ is used as Cadmium source, while Na₂S₂O₃ is used as a sulphur source and ethylene diamine tetra acetic acid (EDTA) is used as a complexing agent.

To record the holograms of CdS thin films onto stainless steel substrate, the plating bath consists of (A₂), (B₂), and (C₂), in the volumetric proportion as 1:4:3 respectively. The pH of the plating bath ranges between 9 to 10.

5.14 Results and Discussion

5.14.1 Surface deformation study of hologram for CdS thin films

The recorded holograms for Cadmium Sulfide thin films for different concentrations with different time intervals are shown in Fig. 5.13, Fig. 5.14 and Fig. 5.15.

Fig 5.13 Holograms of CdS deposited thin film for different deposition time, (i) 110 sec. (ii) 120 sec. (iii) 130 sec. For bath concentration, (A₂).

Fig 5.14 Holograms of CdS deposited thin film for different deposition time, (i) 110 sec. (ii) 120 sec. (iii) 130 sec. For bath concentration, (B₂).
We have estimated the values of thickness of deposited films, mass of the films and stress to substrate for CdS thin films and are reported in table 5.1, 5.2 and table 5.3 for different concentrations solutions.

5.14.2 Thickness measurement of CdS thin films

The thickness of the electrodeposited CdS thin film using the holographic interferometric study of that as deposition time increases, number of fringes onto the substrate increases causing increase in thickness of the film. The thickness of the film has been estimated with the help of Eq. 5.30. The calculated values of thickness of thin films were reported in the Table 5.1, 5.2 and 5.3 for bath concentration \((A_2)\), \((B_2)\) and \((C_2)\). The thickness of CdS thin film varies from 0.94 to 1.58 \(\mu m\) as deposition time varies from 10 to 30 sec for \((A_2)\) bath concentration. For \((B_2)\) and \((C_2)\) bath concentration the thickness increases from 1.26 to 1.53 \(\mu m\) and 1.89 to 2.84 \(\mu m\) respectively as deposition time increases from 110 to 130 sec. The study reveals that increase in bath concentration increases the thickness of CdS thin film. The plot of thickness versus deposition time of CdS thin films for various bath concentrations is shown in Fig. 5.16. As deposition time increases the thickness of CdS thin films increases. It has been observed that with increase in concentration the thickness also increases [62].
Table 5.1 The values of Thickness, mass of the films and stress of CdS thin films to the substrate for different deposition time. for bath concentrations, 0.04 M CdSO$_4$ + 0.4 M Na$_2$S$_2$O$_3$ + 0.06 M EDTA

<table>
<thead>
<tr>
<th>Deposition Time (Sec.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdS thin films deposited (mg)</th>
<th>Stress, $x10^{11}$ (dyne/cm$^2$)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>3</td>
<td>0.94</td>
<td>0.019</td>
<td>0.0116</td>
<td>0.312</td>
</tr>
<tr>
<td>120</td>
<td>4</td>
<td>1.26</td>
<td>0.025</td>
<td>0.0087</td>
<td>0.287</td>
</tr>
<tr>
<td>130</td>
<td>5</td>
<td>1.58</td>
<td>0.031</td>
<td>0.0069</td>
<td>0.272</td>
</tr>
</tbody>
</table>

Table 5.2 The values of Thickness, mass of the films and stress of CdS thin films to the substrate for different deposition time. for bath concentrations, 0.06 M CdSO$_4$ + 0.6 M Na$_2$S$_2$O$_3$ + 0.08 M EDTA

<table>
<thead>
<tr>
<th>Deposition Time (Sec.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdS thin films deposited (mg)</th>
<th>Stress, $x10^{11}$ (dyne/cm$^2$)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>4</td>
<td>1.26</td>
<td>0.025</td>
<td>0.0087</td>
<td>0.283</td>
</tr>
<tr>
<td>120</td>
<td>5</td>
<td>1.58</td>
<td>0.031</td>
<td>0.0069</td>
<td>0.275</td>
</tr>
<tr>
<td>130</td>
<td>8</td>
<td>1.53</td>
<td>0.051</td>
<td>0.0043</td>
<td>0.269</td>
</tr>
</tbody>
</table>

Table 5.3 The values of Thickness, mass of the films and stress of CdS thin films to the substrate for different deposition time. for bath concentrations, 0.08 M CdSO$_4$ + 0.8 M Na$_2$S$_2$O$_3$ + 0.1 M EDTA

<table>
<thead>
<tr>
<th>Deposition Time (Sec.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdS thin films deposited (mg)</th>
<th>Stress, $x10^{11}$ (dyne/cm$^2$)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>6</td>
<td>1.89</td>
<td>0.038</td>
<td>0.0058</td>
<td>0.242</td>
</tr>
<tr>
<td>120</td>
<td>7</td>
<td>2.21</td>
<td>0.044</td>
<td>0.0049</td>
<td>0.165</td>
</tr>
<tr>
<td>130</td>
<td>9</td>
<td>2.84</td>
<td>0.057</td>
<td>0.0038</td>
<td>0.106</td>
</tr>
</tbody>
</table>
Fig 5.16 The variation of thickness of thin film versus deposition time of CdS thin films for \( (A_2) \), \( (B_2) \) and \( (C_2) \) bath concentrations

5.14.3 Stress of CdS thin film to the stainless steel substrate

By measuring the number of fringes, thickness of film and stress to the substrate was determined. He-Ne laser of wavelength 6328 Å was used during the experiment. The reconstructed images of the substrate is similar as given by [63], which confirms that the film grows with tensile stress and the similar behavior has been established for films of various alkali halides, for silver on mica and for gold on glass [64]. The intrinsic stress for CdS thin films were determined from the Eq. 5.32 and are reported in the Table 5.1, 5.2, 5.3 for \( (A_2) \), \( (B_2) \) and \( (C_2) \) bath concentration respectively. It was seen that for the same concentration, as time of deposition increases the intrinsic stress of the film decreases. For \( (A_2) \) bath concentration the CdS film stress to the substrate decreases from 0.0116x10^{11} to 0.0069x10^{11} dyne/cm^{2} with increase in deposition time from 110 to 130 sec. Whereas for \( (B_2) \) and \( (C_2) \) bath concentration the CdS films stress to the substrate decreases from 0.0087x10^{11} to 0.0043x10^{11} dyne/cm^{2} and 0.0058 x10^{11} dyne/cm^{2} to 0.0038 x10^{11} dyne/cm^{2} with increase in deposition time from 110 to 130 sec. Increase in deposition time increases the thickness of thin film which results in decrease in stress of the film to the substrate [65]. The study shows that increase in bath concentration decreases the stress to the substrate.
The plot of calculated stress of CdS thin film versus deposition time for different bath concentrations is shown in Fig. 5.17.

![Graph showing stress vs. deposition time for CdS thin films](image)

Fig 5.17 The variation of film stress with deposition time (i) 110 sec. (ii) 120 sec. (iii) 130 sec. for (A₂), (B₂) and (C₂) solutions of CdS

The variation of thickness, mass deposited and stress of CdS thin film for various fringe width for (A₂), (B₂) and (C₂) bath concentration is shown in Fig. 5.18., 5.19 and 5.20. It has been observed that thickness of CdS thin film increases from the mass deposited onto the substrate increases whereas stress to the substrate decreases with decrease in fringe width.

![Graph showing thickness, mass deposition and stress vs. fringe width](image)

Fig 5.18 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdS thin films for bath concentration (A₂)
Fig 5.19 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdS thin films for bath concentration (B$_2$)

Fig 5.20 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdS thin films for bath concentration (C$_2$)

5.15 Surface deformation study of CdSe thin films

5.15.1 Preparation

To deposit CdSe thin films onto the stainless steel substrate, for bath concentration (A$_3$) = 0.04M CdSO$_4$ + 0.06M SeO$_2$ + 0.1M EDTA, (B$_3$) = 0.06M CdSO$_4$ + 0.08M SeO$_2$ + 0.1M EDTA, and (C$_3$) = 0.08M CdSO$_4$ + 0.1M SeO$_2$ + 0.1M EDTA. for different deposition time, (i) 60 sec. (ii) 70 sec. (iii) 80 sec. Solutions of AR grade CdSO$_4$ is used as cadmium source, while SeO$_2$ is used as a
Selenium source and ethylene diamine tetra acetic acid (EDTA) is used as a complexing agent.

To record the holograms of CdSe thin films onto stainless steel substrate, the plating bath consists of \((A_3)\), \((B_3)\), and \((C_3)\), in the volumetric proportion as 6:6:1 respectively. The pH of the plating bath is 3. The holograms were recorded for three bath concentrations as \((A_3)\), \((B_3)\), and \((C_3)\).

5.16 Results and Discussion

5.16.1 Surface deformation study of hologram for CdSe thin films

The recorded holograms for Cadmium Selenide (CdSe) thin films for different concentrations with different time intervals are shown in fig. 5.22, 5.23 and 5.24. The thickness and stress are determined by using the Eq. (5.30) and tabulated in Table 5.4, 5.5 and 5.6, The Variation of mass of CdSe films deposited on stainless steel substrate, stress to the substrate and fringe width, against the deposition time is as shown in Fig. 5.25, 5.26 and 5.27.

![Holograms](image)

Fig.5.22 Holograms of CdSe deposited thin film for different deposition time, (i) 60 sec. (ii) 70 sec. (iii) 80 sec. For bath concentration, \((A_3)\).
Fig. 5.23 Holograms of CdSe deposited thin film for different deposition time, (i) 60 sec. (ii) 70 sec. (iii) 80 sec. For bath concentration, (B$_3$).

Fig. 5.24 Holograms of CdSe deposited thin film for different deposition time, (i) 60 sec. (ii) 70 sec. (iii) 80 sec. For bath concentration, (C$_3$).

### 5.16.2 Thickness measurement of CdSe thin films

The thickness of the electrodeposited CdSe thin film using the holographic interferometric study of that as deposition time increases, number of fringes onto the substrate increases causing increase in thickness of the film. The thickness of the film has been estimated with the help of Eq. 5.30. The calculated values of thickness of thin films were reported in the Table 5.4, 5.5 and 5.6 for bath concentration (A$_3$), (B$_3$) and (C$_3$). The plot of thickness versus deposition time of CdSe thin films for various bath concentrations is shown in Fig. 5.25. As deposition time increases the thickness of CdSe thin films increases. It has been observed that with increase in concentration the thickness also increases.
Table 5.4. The values of Thickness, mass of the films and stress of CdSe thin films to the substrate for different deposition time for bath concentrations, 0.04M CdSO$_4$ + 0.06M SeO$_2$ + 0.1M EDTA.

<table>
<thead>
<tr>
<th>Deposition Time (Sec.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdSe thin films deposited (mg)</th>
<th>Stress, x10$^{11}$ (dyne/cm$^2$)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>2</td>
<td>0.632</td>
<td>0.015</td>
<td>0.1655</td>
<td>0.371</td>
</tr>
<tr>
<td>70</td>
<td>3</td>
<td>0.949</td>
<td>0.023</td>
<td>0.1103</td>
<td>0.312</td>
</tr>
<tr>
<td>80</td>
<td>4</td>
<td>1.265</td>
<td>0.030</td>
<td>0.0828</td>
<td>0.287</td>
</tr>
</tbody>
</table>

Table 5.5. The values of Thickness, mass of the films and stress of CdSe thin films to the substrate for different deposition time for bath concentrations, 0.06M CdSO$_4$ + 0.08M SeO$_2$ + 0.1M EDTA.

<table>
<thead>
<tr>
<th>Deposition Time (Sec.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdSe thin films deposited (mg)</th>
<th>Stress, x10$^{11}$ (dyne/cm$^2$)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>3</td>
<td>0.949</td>
<td>0.023</td>
<td>0.1103</td>
<td>0.310</td>
</tr>
<tr>
<td>70</td>
<td>4</td>
<td>1.265</td>
<td>0.030</td>
<td>0.0828</td>
<td>0.283</td>
</tr>
<tr>
<td>80</td>
<td>5</td>
<td>1.582</td>
<td>0.038</td>
<td>0.0662</td>
<td>0.275</td>
</tr>
</tbody>
</table>

Table 5.5. The values of Thickness, mass of the films and stress of CdSe thin films to the substrate for different deposition time for bath concentrations, 0.08M CdSO$_4$ + 0.1M SeO$_2$ + 0.1M EDTA.

<table>
<thead>
<tr>
<th>Deposition Time (Sec.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdSe thin films deposited (mg)</th>
<th>Stress, x10$^{11}$ (dyne/cm$^2$)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>4</td>
<td>1.265</td>
<td>0.030</td>
<td>0.0828</td>
<td>0.286</td>
</tr>
<tr>
<td>70</td>
<td>5</td>
<td>1.582</td>
<td>0.038</td>
<td>0.0662</td>
<td>0.277</td>
</tr>
<tr>
<td>80</td>
<td>6</td>
<td>1.898</td>
<td>0.046</td>
<td>0.0551</td>
<td>0.239</td>
</tr>
</tbody>
</table>
Fig. 5.25 The variation of thickness of thin film versus deposition time of CdSe thin films for (A₃), (B₃) and (C₃) bath concentrations

5.16.3 Stress of CdSe thin films to the stainless steel substrate

By measuring the number of fringes, thickness of film and stress to the substrate was determined. He-Ne laser of wavelength 6328 Å was used during the experiment. The intrinsic stress for CdSe thin films were determined from the Eq. 5.32 and are reported in the Table 5.4, 5.5, 5.6 for (A₃), (B₃) and (C₃) bath concentration respectively. It was seen that for the same concentration, as time of deposition increases the intrinsic stress of the film decreases. For (A₃), (B₃) and (C₃) bath concentration the CdSe film stress to the substrate decreases with increase in deposition time. Increase in deposition time increases the thickness of thin film which results in decrease in stress of the film to the substrate. The study shows that increase in bath concentration decreases the stress to the substrate[63-65].

The plot of calculated stress of CdSe thin film versus deposition time for different bath concentrations is shown in Fig. 5.26.
Chapter V

Fig. 5.26 The variation of film stress with deposition time (i) 60 sec. (ii) 70 sec. (iii) 80 sec. for (A\textsubscript{3}), (B\textsubscript{3}) and (C\textsubscript{3}) solutions of CdSe.

The variation of thickness, mass deposited and stress of CdSe thin film for various fringe width for (A\textsubscript{3}), (B\textsubscript{3}) and (C\textsubscript{3}) bath concentration is shown in Fig. 5.27, 5.28 and 5.29. It has been observed that thickness of CdSe thin film increases from, the mass deposited onto the substrate increases whereas stress to the substrate decreases with decrease in fringe width.

Fig. 5.27 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdSe thin films for bath concentration (A\textsubscript{3})
Fig.5.28 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdSe thin films for bath concentration (B₃)

Fig.5.29 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdSe thin films for bath concentration (C₃)

5.17 Surface deformation study of CdTe thin films

5.17.1 Preparation

To deposit CdTe thin films onto the stainless steel substrate, for bath concentration (A₄) = 0.04M CdSO₄ + 0.01M Na₂TeO₃ + 0.1M EDTA, (B₄) = 0.06M CdSO₄ + 0.02M Na₂TeO₃ + 0.1M EDTA, and (C₄) = 0.08M CdSO₄ + 0.03M Na₂TeO₃ + 0.1M EDTA. Solutions of AR grade CdSO₄ is used as cadmium source, while Na₂TeO₃ is used as a Tellorite source and ethylene diamine tetra acetic acid (EDTA) is used as a complexing agent.

To record the holograms of CdTe thin films onto stainless steel substrate, the plating bath consists of (A₄), (B₄), and (C₄), in the volumetric proportion as
5:1:4 respectively. The pH of the plating bath 1. The holograms were recorded for three bath concentrations as \(A_4\), \(B_4\), and \(C_4\).

5.18 Results and Discussion

5.18.1 Surface deformation study of hologram for CdTe thin films

The recorded holograms for Cadmium Telluride (CdTe) thin films for different concentrations with different time intervals are shown in Fig. 5.30, 5.31 and 5.32. The thickness and stress are determined by using the Eq. (5.30), (5.32) and tabulated in Table 5.7, 5.8 and 5.9. The Variation of mass of CdTe films deposited on stainless steel substrate, stress to the substrate and fringe width, against the deposition time is as shown in Fig. 5.33, 5.34 and 5.35

Fig.5.30 Holograms of CdTe deposited thin film for different deposition time, (i) 120 sec. (ii) 180 sec. (iii) 240 sec. For bath concentration, \((A_4)\).

Fig.5.31 Holograms of CdTe deposited thin film for different deposition time, (i) 120 sec. (ii) 180 sec. (iii) 240 sec. For bath concentration, \((B_4)\).
Fig. 5.32 Holograms of CdTe deposited thin film for different deposition time, (i) 120 sec. (ii) 180 sec. (iii) 240 sec. For bath concentration, (C₄).

We have estimated the values of thickness of deposited films, mass of the films and stress to substrate for CdTe thin films and are reported in table 7, 8 and table 9 for different concentrations solutions.

5.18.2 Thickness measurement of CdTe thin film

The thickness of the electrodeposited CdTe thin film using the holographic interferometric study of that as deposition time increases, number of fringes onto the substrate increases causing increase in thickness of the film. The thickness of the film has been estimated with the help of Eq. 5.30. The calculated values of thickness of thin films were reported in the Table 5.7, 5.8 and 5.9 for bath concentration (A₄), (B₄) and (C₄). The plot of thickness versus deposition time of CdTe thin films for various bath concentrations is shown in Fig. 5.33. As deposition time increases the thickness of CdTe thin films increases. It has been observed that with increase in concentration the thickness also increases.
Table 5.7 The values of Thickness, mass of the films and stress of CdTe thin films to the substrate for different deposition time. for bath concentrations, 0.04M CdSO₄ + 0.01M Na₂TeO₃ + 0.1M EDTA.

<table>
<thead>
<tr>
<th>Deposition Time (min.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdTe thin films deposited (mg)</th>
<th>Stress, x10¹¹ (dyne/cm²)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>0.9492</td>
<td>0.021</td>
<td>0.0111</td>
<td>0.310</td>
</tr>
<tr>
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<td>0.0082</td>
<td>0.285</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>1.8984</td>
<td>0.042</td>
<td>0.0055</td>
<td>0.242</td>
</tr>
</tbody>
</table>

Table 5.8 The values of Thickness, mass of the films and stress of CdTe thin films to the substrate for different deposition time. for bath concentrations, 0.06M CdSO₄ + 0.02M Na₂TeO₃ + 0.1M EDTA.

<table>
<thead>
<tr>
<th>Deposition Time (min.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdTe thin films deposited (mg)</th>
<th>Stress, x10¹¹ (dyne/cm²)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>1.2656</td>
<td>0.028</td>
<td>0.0082</td>
<td>0.286</td>
</tr>
<tr>
<td>3</td>
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<td>1.5820</td>
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<td>0.265</td>
</tr>
<tr>
<td>4</td>
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<td>2.2148</td>
<td>0.049</td>
<td>0.0047</td>
<td>0.239</td>
</tr>
</tbody>
</table>

Table 5.9 The values of Thickness, mass of the films and stress of CdTe thin films to the substrate for different deposition time. for bath concentrations, 0.08M CdSO₄ + 0.03M Na₂TeO₃ + 0.1M EDTA.

<table>
<thead>
<tr>
<th>Deposition Time (min.)</th>
<th>Number of Fringes ‘n’</th>
<th>Thickness of film (µm)</th>
<th>Mass of CdTe thin films deposited (mg)</th>
<th>Stress, x10¹¹ (dyne/cm²)</th>
<th>Fringe Width (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>1.5820</td>
<td>0.035</td>
<td>0.0066</td>
<td>0.262</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1.8984</td>
<td>0.042</td>
<td>0.0055</td>
<td>0.195</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>2.8476</td>
<td>0.063</td>
<td>0.0036</td>
<td>0.104</td>
</tr>
</tbody>
</table>
Fig 5.33 The variation of thickness of thin film versus deposition time of CdTe thin films for (A₄), (B₄) and (C₄) bath concentrations.

5.18.3 Stress of CdTe thin film to the stainless steel substrate

By measuring the number of fringes, thickness of film and stress to the substrate was determined. He-Ne laser of wavelength 6328 Å was used during the experiment. The intrinsic stress for CdTe thin films were determined from the Eq. 5.32 and are reported in the Table 5.7, 5.8, 5.9 for (A₄), (B₄) and (C₄) bath concentration respectively. It was seen that for the same concentration, as time of deposition increases the intrinsic stress of the film decreases. For (A₄), (B₄) and (C₄) bath concentration the CdTe film stress to the substrate decreases with increase in deposition time. Increase in deposition time increases the thickness of thin film which results in decrease in stress of the film to the substrate. The study shows that increase in bath concentration decreases the stress to the substrate.

The plot of calculated stress of CdTe thin film versus deposition time for different bath concentrations is shown in Fig. 5.34.
Fig. 5.34 The variation of film stress with deposition time (i) 120 sec. (ii) 180 sec. (iii) 240 sec. for (A₄), (B₄) and (C₄) solutions of CdTe.

The variation of thickness, mass deposited and stress of CdTe thin film for various fringe width for (A₄), (B₄) and (C₄) bath concentration is shown in Fig. 5.35., 5.36 and 5.37. It has been observed that thickness of CdTe thin film increases from, the mass deposited onto the substrate increases whereas stress to the substrate decreases with decrease in fringe width.

Fig. 5.35 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdTe thin films for bath concentration (A₄)
Fig. 5.36 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdTe thin films for bath concentration (B₄)

Fig. 5.37 Stress to substrate, thickness and mass of the deposited films vs. fringe width of CdTe thin films for bath concentration (C₄)
References

49. V. Kohlschutter, E. M. Vivoleamier Zx. Electrochem 24 (1918) 300.
52. H. Blackburn, D. S. Campbell, Phil. Mag. 8 (1963) 923.
64. H. Blackburn, D. S. Campbell, Phil. Mag. 8 (1963) 923.