

SAW Filter Manufacturing Process and Physical Analysis

ABSTRACT In addition to presenting theoretical aspects of the technologies used in semiconductor manufacturing, this report describes the individual steps involved in manufacturing surface acoustic wave filters on a piezoelectric LiNbO₃ substrate. First, a brief description is given of the fabrication of the ceramic carriers onto which the completed SAW dies are bonded. The manufacturing process for the filters on the wafer begins with the deposition of the aluminum filter material. This layer is patterned using lithography and etching. During the subsequent measurement of the completed structures, discrepancies from the originally expected results are observed. These deviations are discussed with the help of the theory presented.

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1 BRIEF INTRODUCTION

Surface acoustic wave (SAW) filters are essential components in modern electronics. They use piezoelectric materials to convert electrical signals into acoustic waves and vice versa, enabling the filtering of specific frequency bands with remarkable precision. SAW filters are indispensable in numerous applications, ranging from mobile phones and televisions to navigation systems and wireless networks. They enable efficient signal management and contribute to the continued development of high-performance communication technologies. This report examines the fabrica-

tion of SAW filters, which takes place in the controlled environment of a cleanroom at Munich University of Applied Sciences. Cleanrooms used in semiconductor manufacturing are designed to ensure an extremely low concentration of particles such as dust, airborne microorganisms, aerosol particles, and chemical vapors. This is necessary because even the smallest particles can cause defects in the tiny structures of integrated circuits. Presenting the relevant theoretical principles, this report explains the manufacturing process, from substrate preparation and photolithography to deposition and etching techniques. The filters produced are examined under a microscope and via SEM after the manufacturing process.

2 MANUFACTURING PROCESSES

2.1 PATTERNING THE CERAMIC CARRIER

The circuit boards onto which the SAW filters are bonded and subsequently measured are ceramic carriers patterned using screen printing, a method of thick-film hybrid technology. Screen printing is a method in which the mesh stretched across a frame is patterned so that it permits a paste—the material used to create the desired structure, such as conductive traces or resistors—to pass through only at the locations corresponding to the desired pattern. During the printing process, the paste is applied to the screen and pressed onto the substrate below using a squeegee; the screen therefore acts as a stencil.

Important Parameters When a screen is patterned for printing a specific design onto a substrate, it must first be ensured that the

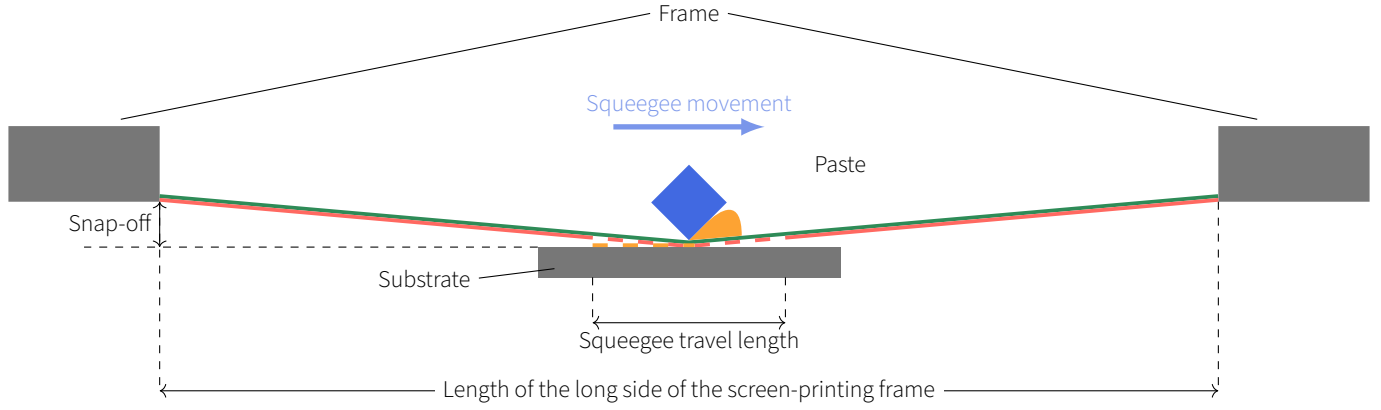


Figure 1 | Schematic representation of printing the ceramic substrate using a screen-printing machine.

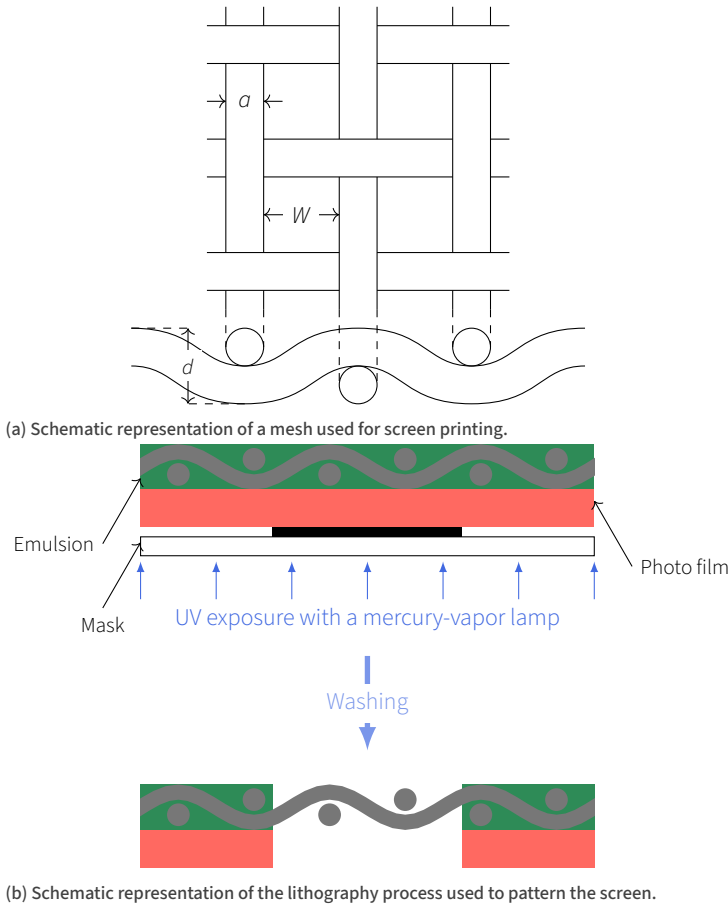


Figure 2 | Patterning the screen.

screen fulfills certain requirements. First, a surface tension of at least 20 N/m should be measurable throughout the mesh. It should also be ensured that the length of the screen is at least three times the length of the squeegee path on the substrate and that its width is at least twice the substrate width. Such dimensions ensure that good print quality and a long service life of the screen are maintained. The print pattern used in this work has dimensions of 50.4 mm × 50.4 mm and is printed onto an aluminum-oxide ceramic substrate (Al₂O₃) using a screen with frame dimensions of 25 cm × 25 cm. The mesh size W and wire diameter a of the screen mesh (see Fig. 2a) are important parameters for determining the thickness of the printed layer. First, the open mesh area must be determined:

$$O = \frac{W^2}{(W + a)^2} 100\% \quad (1)$$

A photo film required for patterning the screen is located on the underside of the screen (see Fig. 2b). The thickness of the printed layer is then given by its thickness d_{UV} and the thickness of the paste contained within the open mesh area, which distributes uniformly over the substrate after the screen is lifted:

$$d = d_{UV} + \frac{O}{100\%} 2a \quad (2)$$

At least three open mesh cells are required to print a complete structure. The screen used in this work has a mesh with a thread angle of 45° and a mesh count of 325 mesh, meaning 325 threads per inch (25.4 mm). The wire diameter is 30 μm. The smallest printable structures of the screen are therefore approximately 200 μm. The open mesh area can be calculated from the mesh count:

$$W + a = \frac{25.4\text{mm}}{325\text{mesh}} = 78 \mu\text{m}$$

$$W = 78 \mu\text{m} - 30 \mu\text{m} = 48 \mu\text{m}$$

$$O = 38\%$$

which yields an expected layer thickness of 37.8 μm.

Patterning the Screen The screen is patterned using a photoemulsion and a photo film. This is the so-called direct/indirect method. It differs from the direct method, in which only the photosensitive emulsion is used, and from the indirect method, in which only a wet photo film is used. At the beginning of the process, the underside of the screen is placed centrally over the photo-sensitive film. The photo film has a carrier layer that is usually glossy; it must therefore be placed facing downward. This carrier layer is removed during a later step. In the next step, the emulsion is applied to the upper side of the screen using a spatula. A squeegee is used to distribute the emulsion evenly over the area beneath which the film is located, applying as uniform a pressure as possible. The film now adheres to the screen through contact with the emulsion. Before the screen can be processed further, the emulsion on the screen must be dried in an oven at 50°C for approximately one hour. The carrier film can then be peeled off. A mask produced using a photoplotter is then placed with its patterned side in direct contact with the photo film and exposed in an exposure unit (see the upper part of Fig. 2b). At the exposed locations, long polymer chains are formed in the photosensitive materials. These chains cross-link and consequently become insoluble in water. The screen is then developed by washing it, causing the film and emulsion to detach from the screen at the unexposed locations (see the lower part of Fig. 2b). After the screen has dried, the area outside the region covered by the film is coated with a screen filler.

Printing the Substrate The screen produced above is used to pattern a ceramic circuit board. Ceramic carriers are used when the desired requirements cannot be met using considerably less expensive organic circuit boards. The main advantages of ceramic carriers are their good stability at elevated temperatures and their good thermal conductivity. A screen-printing machine and conductive paste are required for printing. First, the screen is screwed onto an adapter frame designed for the printing machine and installed in the machine. The screen-printing machine is designed so that several printing operations can be performed consecutively after the printing paste has been applied. The machine uses two different squeegees: a printing squeegee, which moves the paste forward relative to the substrate and thereby forces it through the openings in the screen onto the substrate, and an additional squeegee, which returns the paste to its initial position after each print. The printing process is shown schematically in Fig. 1. To achieve good print quality, care must be taken to select the so-called snap-off distance—the distance between the screen and the substrate—such that the resulting tension in the mesh is sufficient for the screen to separate from the printed structure. On the other hand, the snap-off distance must not be chosen too large, since the resulting tension could distort the printed image or even damage the screen. The substrate must be aligned as precisely as possible beneath the screen. After printing, the substrate, with the still-wet printed paste, is heated in a drying section. Finally, the printed structure on the substrate is fired in an oven.

2.2 CZOCHRALSKI PROCESS

The Czochralski method is currently the most widely used crystal-growth method for producing large, high-purity, single-crystal wafers. The process allows the size and orientation of the crystal to be controlled accurately. In addition to semiconductors, the Czochralski process can also be used to produce metallic single crystals such as palladium, platinum, silver, and gold. The method was developed in 1916 by the Polish scientist Jan Czochralski.

At the beginning of the process, the material from which the single crystal is to be produced is placed in polycrystalline form in a crucible and melted at a temperature slightly above its melting point. Dopant atoms may also be added at this stage if required. In the case of compounds, it must be ensured that the melt is congruent; that is, the composition of the molten compound must be the same as the composition of the compound formed in the solid phase. A small single crystal, known as a seed crystal, with a precisely defined crystal orientation is then attached to the lower end of a rod and immersed below the surface of the melt. The seed crystal is carefully withdrawn from the melt at a controlled speed while being rotated. As it is slowly pulled upward, the melt undergoes a controlled transition into an ordered crystalline solid on the seed crystal under the influence of gravity. The result is a cylindrical block of single-crystal material. For example, the ingot for a 300-mm wafer may be several meters long. The outer diameter of this cylindrical ingot is not uniform and must therefore be machined, for example by grinding, before it can be cut into wafers [1].

Lithium Niobate Crystals Lithium niobate crystals (LiNbO_3) are usually grown using the Czochralski method. LiNbO_3 is particularly common in photoacoustic applications because of its piezoelectric and nonlinear optical properties. In addition to the purity of the LiNbO_3 , the quality of these properties depends strongly

on its Li/Nb composition. During the production of LiNbO_3 using the Czochralski process, temperatures are typically used at which the vapor pressure of Li_2O becomes very high, resulting in the evaporation of lithium. This effect can be minimized by controlling the atmosphere in the growth chamber; in practice, however, it is difficult to completely prevent lithium depletion in the crystal. Lithium contents between 47 and 50 mol% are suitable for applications with stringent requirements on the Li/Nb ratio. The growth of large crystals is also difficult, since increasing the diameter and length can easily lead to cracks in the crystals. With the development of new wireless communication technologies, it is necessary to grow large, high-quality LiNbO_3 crystals to meet the rapidly increasing demand for SAW filters. This remains a significant challenge today [2, 3, 4].

2.3 THERMAL EVAPORATION

Thermal evaporation belongs to the category of physical vapor deposition (PVD). It is one of the oldest methods for depositing thin films onto a wide variety of substrate materials, including polymers, metals, and glass. The deposited films can consist of metals, insulators, or semiconductors. The basic principle of the method is the evaporation of a material in a heated source. The vapor then condenses on all exposed, cooler surfaces within the mean free path of the gas phase. The source may consist of a filament or an electrically heated crucible containing the material to be evaporated. The evaporation rate is determined by the vapor pressure of the starting material at the evaporation temperature. Using tungsten or molybdenum crucibles, temperatures of up to 2800 K can be reached, resulting in high evaporation rates. Even higher temperatures can be achieved by heating the material to be deposited with a focused electron beam, which also prevents contamination from the crucible. The process is carried out in an evaporation chamber under high vacuum ($< 10^{-2}$ Pa) to ultrahigh vacuum ($< 10^{-6}$ Pa). The quality and purity of the deposition increase as the chamber is evacuated more effectively. The most important process parameter for thermal evaporation is the substrate temperature. By varying this temperature, film properties such as porosity, adhesion, surface roughness, and crystallinity can be controlled. The thermal-evaporation process is shown schematically in Fig. 4b.

The main advantages of thermal evaporation are its high deposition rate and the large film thicknesses that can be produced. A significant disadvantage is that although flat surfaces can be coated effectively, the sides and bottoms of deeper or more complex structures may not be adequately coated or may not be reached at all. Sputtering, another widely used physical vapor-deposition method, offers an alternative to thermal evaporation. In sputtering, the material to be deposited is bombarded with energetic particles, usually ions from an inert-gas plasma. Atoms or molecules are ejected from the target material, travel through the vacuum, and are deposited on the substrate. Both methods are compared in Tab. 1, which was adapted from [5].

Other methods classified as physical vapor deposition include cathodic arc deposition, which is widely used in industry, ion plating, laser-beam ablation, and thermal spraying. In addition to PVD, there are numerous other coating methods, including chemical vapor deposition (CVD) and epitaxial film growth. The choice of method may depend strongly on the materials being used. In all cases, the requirements—such as film thickness, uniformity,

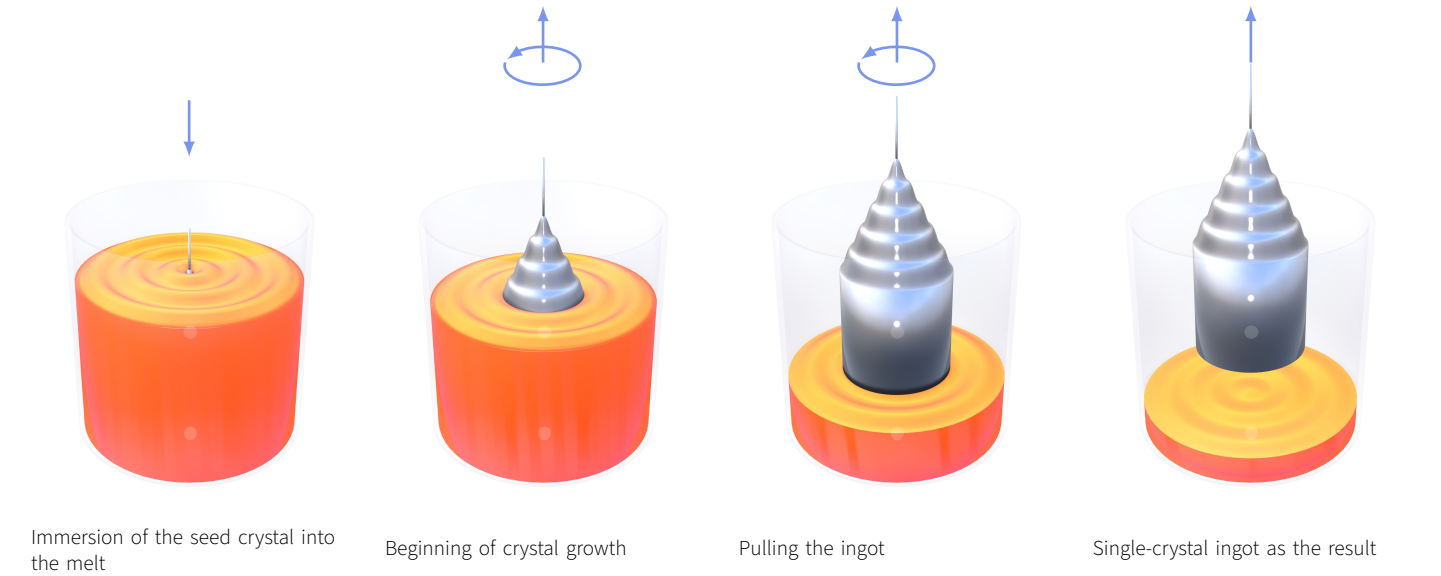


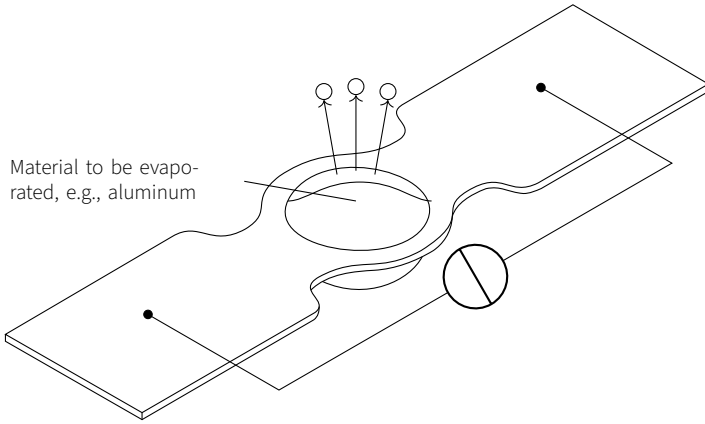
Figure 3 | Illustration of the Czochralski process. The Czochralski process is a materials-engineering method for producing single-crystal materials. The process takes place inside an evacuated growth chamber.

	Evaporation	Sputtering
Deposition rate	up to $\mu\text{m/s}$	$<1\text{ nm/s}$
Material selection	limited	almost unlimited
Purity	very good at high vacuum	impurities possible
Substrate heating	low	can be high
Stoichiometry	difficult, even with multiple sources	easier
Changing film material	easy	expensive
Material decomposition	high	low
Scalability	good, except with electron beams	good
Equipment cost	low	high
In-situ thickness control	easy	difficult
Lift-off masking	easy	difficult
Step coverage	poor	good; can be controlled

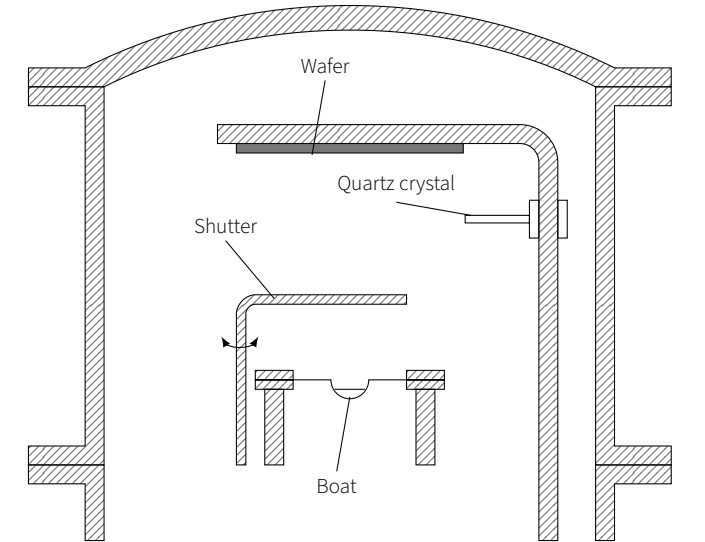
Table 1 | Comparison of thermal evaporation and sputtering.

and purity—should be weighed against the cost [5, 6, 7].

Cleanroom Experiment In this experiment, aluminum interdigital transducers (IDTs) are fabricated on a piezoelectric LiNbO3 wafer. For this purpose, an aluminum layer is thermally evaporated onto the wafer surface and subsequently patterned using lithography. The experimental setup is shown schematically in Fig. 4b. First, the wafer is placed in a ring-shaped holder in the upper part of the vacuum chamber, with the surface to be coated facing vertically downward. Consequently, an uncoated edge corresponding to the size of the holder remains on the wafer after coating. In the lower part of the vacuum chamber are two so-called boats—very small crucibles—made of tungsten, which has a considerably higher melting point than aluminum (see Fig. 4a). The aluminum, in the form of pellets, approximately three per boat, is evaporated by passing an electrical current in the ampere range through the boats via two electrical contacts. The boats are not located exactly beneath the wafer surface, so a slightly nonuniform film thickness is to be expected. Shutters are positioned be-



(a) Boat. These boats are typically made of tungsten.



(b) Schematic setup for thermal evaporation.

Figure 4 | Thermal evaporation.

tween the wafer and the boats; these allow the start and end of the evaporation process to be controlled. The vacuum chamber also contains an electrode used to clean the surface with plasma before evaporation. The evaporation rate is measured in situ using a quartz crystal monitor. Once the vacuum chamber is closed,

pumps and a control unit evacuate the chamber. When the target pressure of approximately 5×10^{-6} mbar is reached, the current is switched on and the boats are heated. As the quartz crystal is also coated, its resonant frequency changes with increasing film thickness. The control unit converts this change into an evaporation rate, which can be determined accurately if the system is well calibrated. Once the desired evaporation rate—approximately $5 \text{ \AA/s}$ in this case—is reached, the shutters are opened until the film thickness on the wafer is between 200 and 400 nm. In principle, a smaller film thickness could be selected. In this case, however, the IDTs are contacted with bond wires during a later step, and a film that is too thin could cause damage to the structures. To maintain a constant evaporation rate, the control unit reduces the current as the mass in the boats decreases, thereby keeping the temperature constant. The evaporation process is stopped by closing the shutters and switching off the current. The chamber is then slowly vented, after which it can be opened and the aluminum-coated wafer can be removed. When opening the chamber, care must be taken to ensure that the pressure inside the chamber does not rise abruptly, since this could damage the pumps.

2.4 LITHOGRAPHY

Lithography is used in the manufacture of semiconductor devices to create a large number of patterns simultaneously on the surface of a substrate wafer. This is achieved using ultraviolet light, a mask, and a photoresist. Masks are usually made of high-purity quartz glass. Their fabrication is very complex and considerably more time-consuming than the actual lithography process. They are generally produced using an electron-beam writer, which writes the structures to be transferred onto the mask. There are two main categories of photomasks: binary masks and phase-shift masks. As the name suggests, a binary mask consists of two different regions: one transparent to the exposure light and one opaque region. The structure of a phase-shift mask (PSM) is considerably more complex. These masks are designed so that the transmitted light experiences a phase difference in certain regions relative to light rays from neighboring regions. The resulting interference effects make higher resolutions possible. Halftone and alternating PSMs (see Fig. 5) are common designs, with alternating PSMs being the most frequently used today. Because of their complexity, these masks are considerably more expensive to manufacture than binary masks and may require additional alignment steps during the lithography process. A photoresist is generally a light-sensitive, chemically resistant polymer. A distinction is made between positive and negative photoresists: in a positive resist, the exposed regions are removed during development, whereas the exposed regions remain in a negative resist.

At the beginning of the lithography process, the wafer is placed in a spin coater and rotated. A small amount of photoresist is deposited onto the wafer (sometimes by spraying), which creates a uniform, thin film on the surface. To improve the adhesion between the photoresist and the wafer surface, an adhesion promoter layer is typically applied to the surface before the resist is applied. After spinning, the coated wafer is dried on a hotplate, which removes most of the solvent from the photoresist and improves adhesion. The mask with the desired structures is then aligned over the wafer and exposed to light—usually ultraviolet light—which passes through the transparent regions of the mask and alters the chemical structure of the photoresist in these regions. Three different exposure methods are used in photolithog-

raphy: contact, proximity, and projection lithography.

Contact Lithography In contact lithography, the photomask is brought into direct contact with the photoresist-coated wafer. During exposure, ultraviolet light passes through the mask and transfers the pattern directly onto the photoresist. This method achieves high resolution because the distance between the mask and photoresist is minimal, which prevents diffraction and scattering effects of the light. However, a disadvantage of this method is that the mask can be damaged due to direct contact, and defects in the patterns can occur due to particle deposits on the wafer surface.

Proximity Lithography Proximity lithography is similar to contact lithography, but the mask does not touch the wafer surface. Instead, there is a small gap (up to a few tens of micrometers) between the mask and the photoresist. This method prevents mask damage and pattern defects caused by direct contact with the wafer. However, this comes at the cost of resolution, since light diffraction and scattering are more pronounced due to the gap between mask and photoresist.

Projection Lithography Projection lithography is the most commonly used method today. In this method, an optical lens system is located between the mask and the wafer. This system typically projects the mask image onto the photoresist, reducing its size by a factor of 5 to 10. Unlike the previous methods, the wafer is exposed in segments one after another. After exposing one section of the wafer, the substrate is moved a specific distance to expose a new, unexposed area. This so-called step-and-repeat process is repeated until the entire wafer is patterned with the mask image. The equipment used for this purpose can be either a stepper or a scanner. A stepper produces a rectangular image on the wafer. Because of the large field size used, lens errors reduce the resolution of small structures. A scanner, on the other hand, exposes only a strip of the image onto the wafer. The wafer and mask must therefore be scanned relative to each other. Since a much smaller field size is used, lens errors (which occur at the edge of the lens system) are greatly reduced. Scanners are the standard for technologies in the deep submicrometer range. These methods

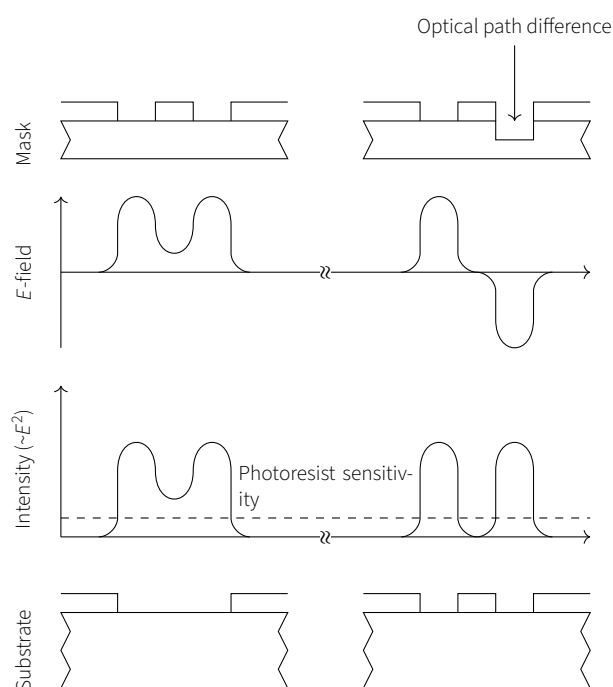


Figure 5 | Operating principle of an alternating phase-shift mask.

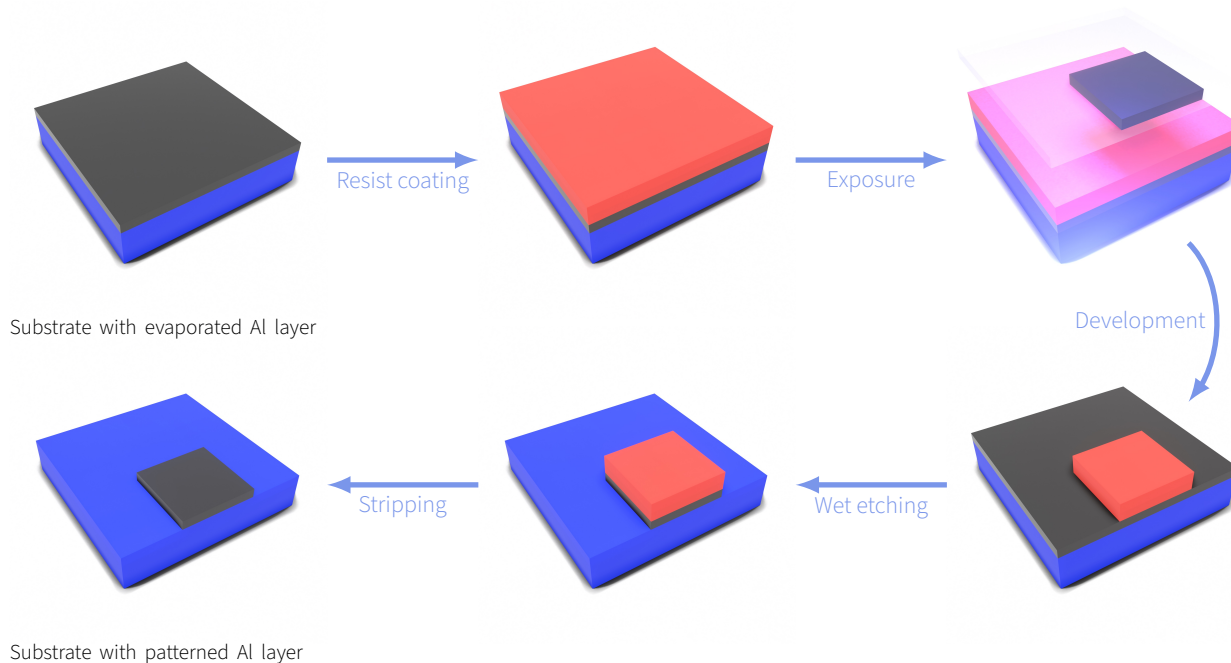


Figure 6 | Individual process steps in patterning the aluminum layer on the LiNbO₃ wafer (lithography and etching).

require monochromatic light. They allow for much higher resolutions than the previously mentioned methods, enabling the fabrication of considerably more complex and smaller components. However, this method is also more expensive and yields fewer chip structures per wafer. The resolution achievable in projection lithography is given by Abbe's diffraction limit:

$$d = \frac{\kappa_1 \lambda}{\text{NA}}$$

Here, $\text{NA} = n \sin \theta$ is the numerical aperture of the projection lens, and λ is the wavelength of the light used. The factor κ_1 is very important for projection lithography. Its value is determined by the quality of the optics, the photoresist, and the mask. The value is limited by diffraction effects and can be at best 0.25. The structure sizes currently produced with this method are fractions of the wavelength used. Therefore, the wave nature of light must be taken into account even in this method. To achieve high resolutions, specialized exposure patterns and complex computational models are developed [1, 8, 6, 9, 10].

After exposure, the substrate is immersed in a developer solution that selectively removes the regions of the photoresist that were either exposed or not exposed (depending on whether a positive or negative photoresist was used). This reveals the patterned surface through the gaps where the photoresist has been washed away. When patterning metal layers, the lithography process can be applied either after the wafer surface has been coated with the metal or before it is coated. In the latter case, the structures are created using the so-called lift-off process. The metal layer is deposited over the entire surface, and the remaining photoresist is removed by lifting off the excess deposited material. This is typically done by immersing the substrate in a solvent that dissolves the photoresist but does not attack the deposited thin film. If the surface was already coated with the metal beforehand, structures are created through etching. The remaining photoresist serves as a mask to protect regions where the metal should not be removed.

Cleanroom Experiment—Resist Coating The aluminum layer previously evaporated onto the LiNbO₃ wafer is to be patterned into

the desired IDT patterns using an etching process. The goal of the lithography step is therefore to create a mask for the subsequent etching process. Fig. 6 shows the process schematically. First, a photoresist layer—the material for the etching mask—must be applied to the entire aluminum layer. To ensure good adhesion of the resist to the aluminum, a very thin adhesion-promoter layer is first applied to the wafer surface. This step is necessary because the photoresist does not adhere well to the LiNbO₃ surface in the same way that water does not adhere to a hydrophobic surface. The process is carried out using a spin coater, a device in which the wafer is held on a rotationally electric spindle via vacuum, with controllable rotation speed. In our procedure, an adhesion promoter is first applied by pipetting 1 mL vertically over the center of the wafer at 500 rpm for the first 10 seconds. The rotation speed is then increased to 5000 rpm and held constant for approximately 30 seconds. During this time, the material is distributed evenly over the entire surface by centrifugal force. The amount of material deposited and the rotation speed determine the layer thickness, which in this case is in the low nanometer range and will not affect the lithography process. The wafer is then removed from the spin coater and dried on a hotplate, with the temperature initially increased in steps. When the hotplate reaches 120 °C, the temperature is held constant, and the wafer is removed after approximately one minute. Stepwise temperature increase is necessary because the substrate material is piezoelectric. Abrupt temperature changes can cause large mechanical and electrical stresses within the material, which can manifest as sparks and lead to changes in electrical properties that could degrade the wafer's performance. After the wafer has cooled for approximately one minute, 1.5 mL of photoresist is applied using the same parameters as the adhesion promoter (first 10 seconds at 500 rpm, then 30 seconds at 5000 rpm). The wafer is dried in the same manner as before. The temperature is held at 100 °C at high temperatures, because the resist becomes brittle at higher temperatures. This brittleness can change the exposure parameters and cause problems when removing the photoresist during development and etching.

Cleanroom Experiment—Exposure After the photoresist on the wafer surface has hardened, it can be exposed using an exposure

unit and the previously prepared photomask. Positive resist is used in this process, so the IDT structures appear as light-opaque regions on the mask. The mask must be installed in the exposure unit's holder so that the SAW structures are aligned in a direction where the surface-wave propagation is perpendicular to the wafer flat. This ensures that the surface-wave velocity at which the filter was designed operates correctly. An automated mechanical stop identifies the wafer flat and rotates the wafer so that the flat points downward, ensuring precise alignment between mask and wafer. During exposure, the mask and wafer are brought into direct contact; this is therefore contact lithography. Since the structure sizes are in the lower micrometer range, a high resolution of the photoresist structures is expected. The exposure time is 10 seconds in this case. The light source is a mercury-vapor lamp whose most important emission lines are at 365 nm, 405 nm, and 435 nm, where the photoresist is most sensitive. After the wafer is removed from the exposure unit, it remains optically unchanged. To remove the exposed positive photoresist, it must be developed.

Cleanroom Experiment—Development The wafer is first placed in a beaker with the exposed photoresist layer facing upward. This prevents the wafer from floating on the developer solution. The developer solution, which is formulated specifically for this photoresist layer thickness, is carefully measured. It is important to use sufficient developer solution to dissolve all exposed regions. In our case, 40 mL is used. During development, which takes approximately 40 seconds, the solution must be kept in constant motion to transport dissolved photoresist away from the surface and to remove air bubbles that could impede the chemical process. The wafer should be removed from the beaker in time and quickly rinsed with deionized water to avoid dark decay—unwanted attack on unexposed regions. Finally, the wafer is dried in a spin coater.

2.5 ETCHING TECHNIQUES

After the photoresist on the substrate surface has been patterned, an etching technique is needed to remove the coating that is not protected by the resist. In general, etching techniques are divided into wet-etching and dry-etching methods. In the case of wet etching, the use of photoresist as a protective mask is limited to producing flat etches.

Wet Etching Wet etching is based on a chemical redox reaction that occurs on the surface of the material being etched. The wafer is immersed in a bath containing a chemical etchant. The etchant is reduced on the surface while the surface material is oxidized, forming soluble ions containing the surface material. These ions then diffuse away from the reaction surface. With the right choice of etchant, all materials used in practice can be etched. Wet etching is isotropic when chemical reactions spread in all directions within the material at the same rate. In this case, undercutting beneath the photoresist and rounded edges are observed. The etching process is usually controlled by time. Alternatively, the process can be stopped once the material beneath the layer being removed becomes visible, provided it differs from the etched material. The undercutting and rounding become more pronounced the longer the etching process continues, so precise timing is essential. Isotropic etching can be a limitation when creating very fine and precise patterns; however, it is suitable for many applications where these characteristics are acceptable. For anisotropic wet etching of silicon, a mixture of hydrofluoric acid (HF), nitric

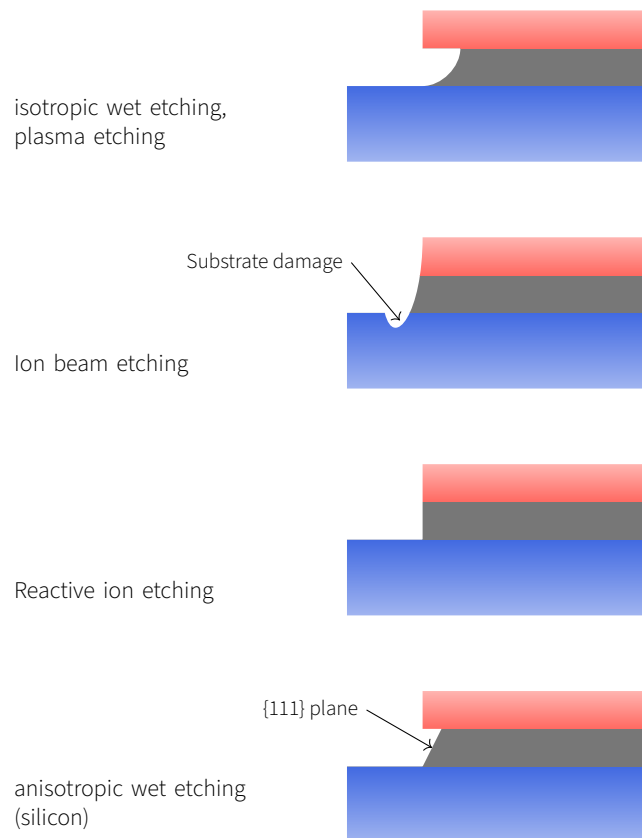


Figure 7 | Etch profiles of various etching methods.

acid (HNO₃), and acetic acid (CH₃COOH) is typically used. This results in much faster etching rates in the {100} and {110} directions than in the {111} direction. The reason is that silicon atoms on different crystal planes have different activation energies for the etching reaction. Wet etching is often preferred because of its simplicity, relatively low cost, and high etching rate.

Dry Etching In dry etching, no chemical solutions are used. Instead, the surface is treated with (reactive) gases. Within a vacuum chamber, a plasma—a mixture of radicals and ions—is brought into contact with the material surface. When the plasma strikes the surface, material removal occurs through a combination of chemical reaction and, in part, physical sputtering. When the removal mechanism is based solely on chemical reactions, the process is called plasma etching. The most widely used etching method is reactive ion etching (RIE), in which removal is enhanced by the physical impact of ions on the surface. The plasma is accelerated toward the substrate by an applied voltage. A process based primarily on physical sputtering by ion impacts is ion-beam etching (IBE), in which a focused ion beam directed at the substrate sputters away the material. The isotropy of the etching can be adjusted by changing the pressure within the chamber. Low pressure leads to high anisotropy, which prevents undercutting. However, this comes at the cost of selectivity, which can lead to unwanted material removal and substrate damage. To improve selectivity, other parameters such as plasma composition and temperature can be adjusted. Reactive ion etching can be combined with the so-called Bosch process to produce very deep, highly anisotropic etch profiles. In this process, the substrate is alternately etched and passivated with a protective layer on the sidewalls of the etch profile. In the next etching step, material is removed only in the depth direction. In dry-etching processes, volatile byproducts are produced when material is removed from the surface. Ideally, these byproducts are evacuated from the etching chamber by the

vacuum system. In practice, not all byproducts escape the chamber; some re-deposit on parts of the surface, such as the side-walls of etched structures. This unwanted re-deposition can distort the etch profiles and must therefore always be monitored. As structures become smaller, dry etching has become the preferred method over wet etching because it provides better control over the etching process, higher resolution in patterning, and the ability to etch thin layers with high aspect ratios. Tab. 2 provides a rough comparison of both methods.

	Wet Etching	Dry Etching
High vertical walls	not possible	easily achieved
High aspect ratio structures	limited	almost unlimited
Feature size	very limited	small
Etch rate	very high	rather low
Re-deposition	none	present
Substrate damage	none	possible
Undercutting	pronounced	can be controlled
Cost	low	can be high

Table 2 | Comparison of wet etching and dry etching.

After the etching process is complete, the wafer is removed from the etch bath, and the remaining photoresist is removed using a solvent or another chemical solution. The wafer is then thoroughly rinsed with deionized water to remove all chemical residues and subsequently dried [11, 12, 13, 14].

Cleanroom Experiment—Wet Etching and Stripping The exposed aluminum layer on the LiNbO3 wafer is removed in this experiment by a wet-etching process. As is common practice, a phosphoric-acid-based solution at 40 °C is used. Temperature affects the etch rate and the uniformity of the process. If the etching takes place at too high a temperature, the photoresist may also be etched. The chemical reaction on the aluminum surface produces, among other things, aluminum phosphate and hydrogen gas. To transport the reaction products away from the surface, the solution is kept in constant motion over the wafer surface. With this method, an etch rate of 300–500 nm/min can be achieved. Before starting the etching process in a beaker preheated with the etch solution, a second beaker filled with deionized water is prepared to allow the etching process to be stopped quickly. In our procedure, the etching is performed by sight; that is, as soon as the LiNbO3 surface becomes visible—which happens within a few tens of seconds for a layer thickness of approximately 200 nm—the process is stopped by immersing the wafer in deionized water. This etching process is isotropic, so undercutting cannot be avoided. However, care must be taken to minimize the undercutting because it increases the longer the etching process continues. In the best case, the undercutting is equal to the etch depth. Therefore, we can expect the structures to shrink by at least 200 nm on all sides from the originally planned geometry. After the wafer is dried in a spin coater, the photoresist remaining on the surface is removed in a resist stripper using acetone and isopropanol. Acetone removes the resist while isopropanol cleans the surface of acetone [15].

2.6 WIRE-BONDING TECHNIQUES

Wire bonding, also called wire bonding, is a connection technique in which two metallic bodies—typically so-called bond pads—are

connected by a metallic wire so that electrical current can flow between them. It is a type of solid-phase welding in which the wire (and possibly the surface of the contact point) is plastically deformed while being brought so close to the contact point that interatomic interaction forces bond them together. Usually, contaminants such as air, carbon-containing compounds, and oxides are present on the surfaces of the bond pads and the wire. These must be removed during this process to establish good contact and an electrically conductive connection. Three different methods are distinguished: thermosonic bonding, ultrasonic bonding, and thermosonic bonding.

Thermocompression Bonding In thermocompression bonding, the primary parameters are temperature and pressure, which provide the activation energy at the bond site needed to create interatomic bonding forces. The temperature is usually provided by heating the entire component and is typically at least 300 °C. For many applications today, these temperatures can be harmful to the components. In addition, the bonding time is relatively long (> 100 ms), which is why thermocompression bonding is rarely used anymore.

Ultrasonic Bonding Unlike thermocompression bonding, ultrasonic bonding is performed at room temperature. The main parameter is the ultrasonic energy supplied to the wire through an ultrasonic transducer while it is brought into contact with the bond pad. The ultrasonic energy provides the activation energy required for interatomic bonding. For example, an ultrasonic power density of 50 W/cm² can produce the same interactions as a temperature of 600 °C. However, excessively high ultrasonic frequencies can cause crater formation on the substrate, which makes this method unsuitable for mechanically sensitive devices.

Thermosonic Bonding Thermosonic bonding is a combination of thermocompression bonding and ultrasonic bonding. The temperatures used are in the range of approximately 120 °C to 220 °C. By using ultrasound, the temperature can be kept relatively low, preventing damage to components. For bonding gold wires to semiconductors, this method is currently the most widely used.

The three methods are compared in Tab. 3, adapted from [16]. Depending on how the first contact of a wire-bond connection is made, a distinction is made between wedge bonding and ball bonding.

Wedge Bonding Wedge bonding is one possible implementation of ultrasonic bonding and thermosonic bonding. The wire is guided through a wedge-shaped tool that holds it in position. The bonding process begins at the first bond site, typically a bond pad on the die. The bonding tool descends onto the bond pad and presses the wire together while ultrasonic energy is applied.

	Thermocompression	Thermosonic	Ultrasonic
Ultrasonic power	no	yes	yes
Bond force	high	low	low
Temperature	>300 °C (high)	120–220 °C (moderate)	room temp.
Bond time	long	short	short
Wire material	Au	Au	Au, Al
Pad material	Au, Al	Au, Al	Au, Al
Contamination	severe	moderate	moderate

Table 3 | Comparison of wire-bonding techniques.

In thermosonic bonding, the heat typically comes from the tool holder of the machine, but in some cases it can also come from a heated bonding tool or capillary. Once the wire is bonded to the pad, the tool moves upward and toward the second bond site, typically located on a substrate or lead frame. To reduce the tensile forces acting on the bonded connections, the bond is made in the shape of an arc. For this purpose, the tool is first advanced slightly beyond the second bond location so that the length of the wire pulled from the machine is slightly longer than the distance between the pads. As the tool returns to the second bond site, an arc forms. The tool then descends and bonds the wire to the pad as in the first step. The wire is then clamped, cut, and the tool is withdrawn. Care must be taken with this method to ensure that the wire is aligned in an approximately straight line from the first to the second bond site before it is bonded. In industrial semiconductor-chip manufacturing, this is a time disadvantage. Automated wedge-bonding systems achieve about 4 bonds per second. Wedge bonding is well suited for gold and aluminum wire connections. The porous aluminum oxide layer on aluminum wires can be easily removed by ultrasonic waves.

Ball Bonding Ball bonding is one possible implementation of thermocompression bonding and thermosonic bonding. The wire is guided through a capillary, with the wire tip extending slightly beyond the capillary in the initial position. It is heated by a heated surface or an electrical spark from a charged electrode in the immediate vicinity, causing the wire end to melt. Due to surface tension, a small sphere forms. The capillary approaches the first bond site, and the molten wire tip is pressed onto the bond pad through the capillary, creating the first bond connection, optionally with the aid of ultrasound. The capillary then moves upward slightly and travels to the second bond site. The second bond connection is made as in wedge bonding. After ball bonding, the wire can be moved in any direction, which is a major advantage over wedge bonding. Autobonders achieve a speed of about 10 bonds per second with this method. Gold is typically used as the wire material in ball bonding because, unlike aluminum, it does not form an oxide layer during the melting process, which would severely negatively impact the quality of the bond. In principle, aluminum can be used as long as the process uses pure aluminum and takes place in an evacuated environment.

[16, 17]

Modern Wire Bonding Due to its low cost and increased flexibility, wire-bonding technology remains the preferred interconnection technique for most applications. Consequently, more than 80% of semiconductor packages are still assembled using wire-bonding technology today. For packaging integrated systems such as System-in-Package (SiP) architectures and various types of memory devices, wire bonding is by far the most commonly used and cost-effective bonding method. To keep the package volume as small as possible, integrated memory devices such as DRAM and flash memory (NOR and NAND) are stacked vertically (stacked memory). The individual memory layers are then carefully bonded to each other on the steps using wire-bonding technology and subsequently connected to the package substrate, creating a coherent assembly (see Fig. 8). These memory devices occupy the majority of the package volume and are being continuously miniaturized and made more powerful by increasing the number of layers. Reducing the height of the wire-bond arcs also plays an important role in reducing the overall package height. Arc heights of less than 35 μm are targeted. As height decreases, the tensile strength of the bond site must increase. The industry has standardized designs with 16 layers. Increasingly smaller con-

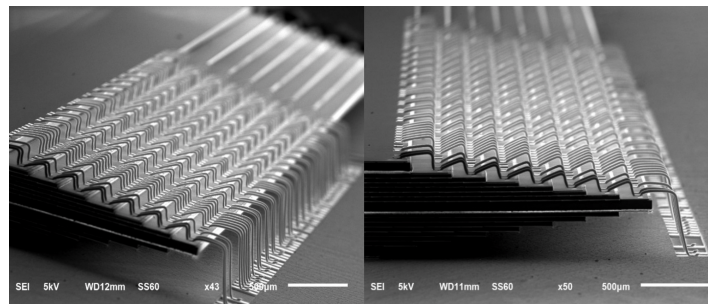


Figure 8 | Example of a 16-layer die stack. From [20], the thickness of a die including DAF (die attach film) is 28 μm .

sumer electronics present a challenge for non-destructive bonding of these stacks. For example, the memory stack in the Apple Watch has a package height of 0.56 mm [18, 19, 20].

Experiment—IDT Circuit Board Bonding Initially, wire bonding is practiced on a dummy substrate containing bond pads arranged in a grid pattern. This is done with a wedge bonder using an aluminum wire with a diameter of 250 μm (heavy-wire bonder). The ultrasonic power and application time for the first and second bonds, as well as the force applied, can be adjusted. Afterward, the process is repeated on a more modern wedge-bonding machine, also using a 250 μm aluminum wire. With this machine, the movement of the bonding tool from the first to the second bond site is automatic. After practicing bonding with dummy substrates, the SAW dies bonded to the circuit board are then bonded. This is done with a ball-bonding machine using gold wire with a diameter of 25 μm . The bonding technique used is thermosonic bonding. The bond connections to be made are shown schematically in Fig. 13. The large trace area is the ground connection. As can be seen in Fig. 13c, three identical bond connections were made at each location. This is merely a safety measure to ensure that an electrical connection exists between the two areas in case one bond connection is damaged.

3 MEASUREMENTS

3.1 REFLECTOMETER

A reflectometer is used to measure the thickness of the photoresist layer applied to the surface. A reflectometer directs a light beam onto a sample surface and measures the intensity of the reflected light. The operating principle is sketched in Fig. 9. When light strikes the layer applied to the wafer, part of the light is reflected from the surface, and part penetrates through the film and is reflected at the interface between the film and the underlying substrate. The light rays reflected from the surface and the interface interfere with each other, producing different measured intensities depending on the layer thickness. This intensity information can be converted to a layer thickness.

In this work, an aluminum layer is located beneath the applied photoresist layer. Light is therefore reflected much more strongly at the aluminum interface than at the photoresist surface, making the measurement difficult. Therefore, instead of measuring the photoresist layer on the LiNbO₃ wafer, a photoresist layer applied in exactly the same manner to the SiO₂ surface of a silicon wafer is measured. To obtain an accurate layer thickness, a reference measurement must first be made, and the refractive indices of the

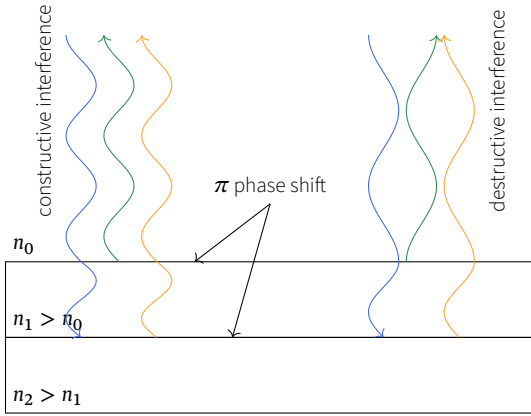
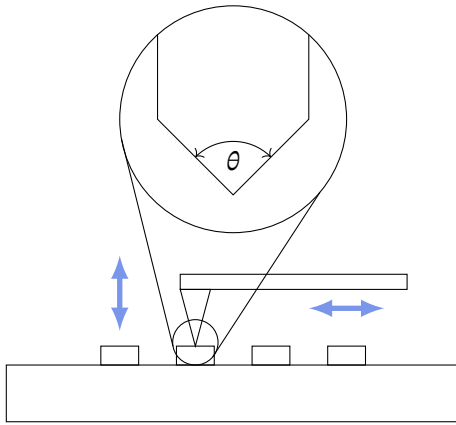
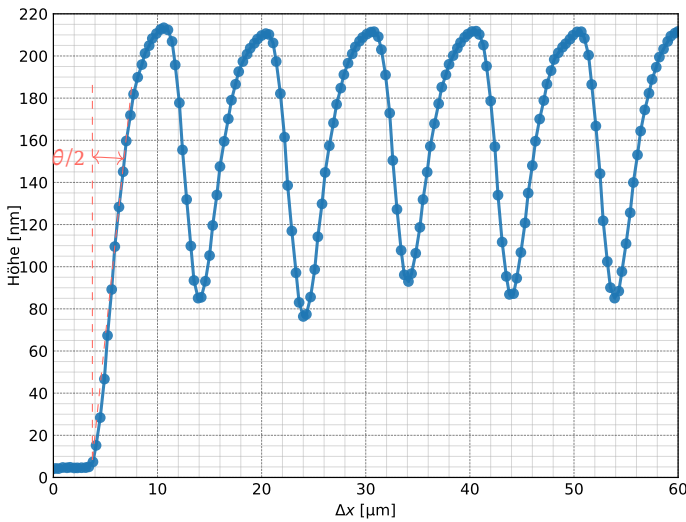


Figure 9 | Operating principle of a reflectometer.



(a) Operating principle of a profilometer.



(b) Profilometer measurement data across the finger structures of an IDT.

Figure 10 | Profilometer

relevant layers must be entered into the measurement system. In this case, these are Si ($n = 3.8714$), SiO₂ ($n = 1.4571$), and resist ($n = 1.6233$). A layer thickness of 1850 nm is measured.

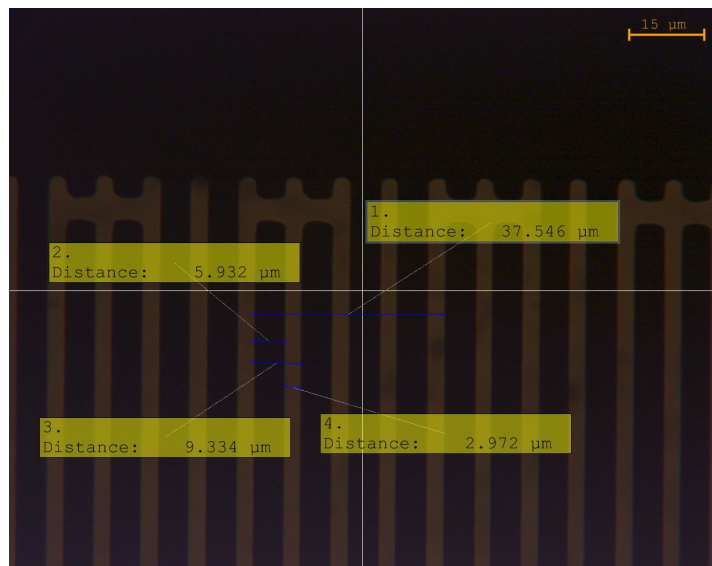
3.2 PROFILOMETER

Since aluminum is opaque to visible light, the aluminum layer on our wafer cannot be measured using reflectometry. It is therefore determined using a profilometer. A profilometer is an instrument for measuring surface profiles, roughness, and the thickness

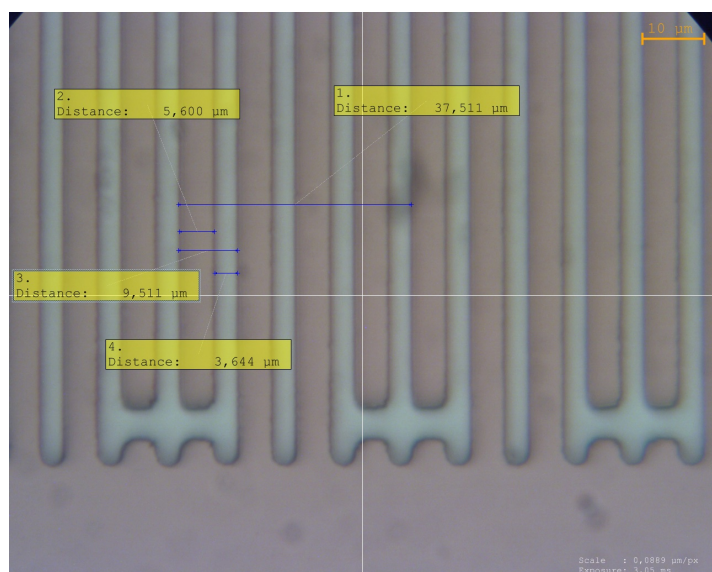
of thin films and structures on a substrate. A needle attached to an arm touches the surface. The needle moves in a straight line across the wafer surface. When the needle encounters changes in surface topography (e.g., at the edges and top of a structure), the arm with the needle moves up and down (see Fig. 10a). The vertical movement is recorded, and the collected data yield a profile of the surface features along the measurement path. To measure the thickness of a structure, the profilometer can measure the distance between the baseline of the surface (substrate) and the top of the structure resting on the substrate. In this work, an arbitrary IDT on the finished processed wafer is measured. Examining the recorded layer thickness in Fig. 10b, it can be seen that the target thickness of 200 nm was achieved very well. According to the measurement, the aluminum layer height is approximately 210 nm. It is also apparent from the recorded data that the captured edge is not perfectly vertical. This can be expected given that the needle tip is many times larger than the measured structure. At the gaps between the IDT fingers, the needle did not capture the exact dimensions, since the needle-tip angle was too large to reach the LiNbO₃ substrate surface at these locations. The recorded profile represents, in good approximation, the path traced by the needle tip. Mathematically speaking, the recording describes the convolution function of both geometries. In principle, the layer thickness could also be measured immediately after the aluminum-layer evaporation process by measuring the step at the edge of the wafer, which is created by the holder in the evaporation chamber. In this case, one would assume that the layer thickness varies relatively little over the entire surface. One advantage of this measurement method is direct measurement, as no information about the materials present (e.g., refractive index as required for reflectometry) is fundamentally necessary. A disadvantage, however, is that this method scratches the structures. For such a measurement, test structures are often placed on the wafer. Depending on the application, this unused space on the wafer can result in a cost disadvantage.

3.3 MICROSCOPY

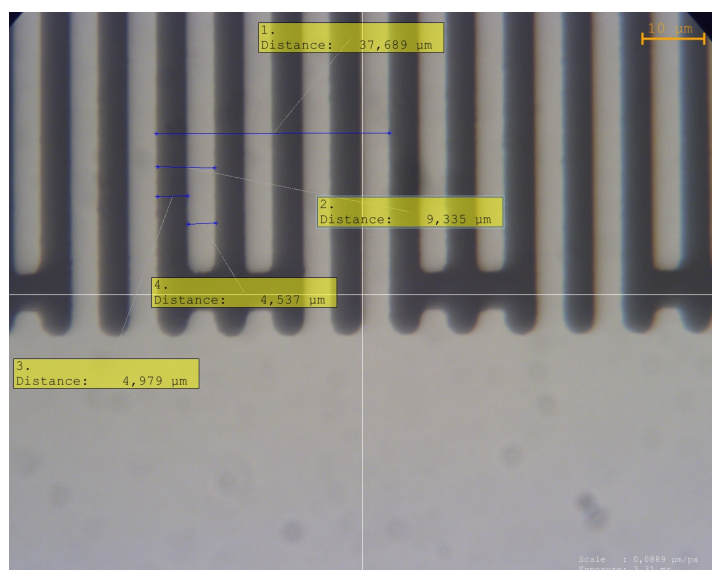
Measurement Setup and Observations An IDT structure on the mask used for lithography is first examined using a transmitted-light microscope. In this case, it is an IDT from the filter designated “C31”. This filter was designed for a center frequency corresponding to a surface-wavelength of 37.6 μm . The measurement is performed at 100 $\times$ magnification via software on a computer, with the image displayed live on the screen. A distance is measured by positioning a line appropriately with the mouse. The software then converts the line length on the screen to the actual distance on the sample. The measurement is shown in Fig. 11a. Here, transparent areas on the mask appear bright, while the chromium structures appear dark. It is initially evident that the chromium structures are noticeably wider than the gaps between them. The chromium structures were presumably deliberately made wider to compensate for the undercutting that occurs during wet etching. It is also apparent that the right-angle corners of the structures are rounded. These rounded corners were likely produced by the electron beam of the mask-writing tool, whose profile corresponds to a radially symmetric Gaussian profile. When the electron beam strikes a surface (e.g., photo-sensitive resist), it produces a circular structure. Straight edges can therefore be reproduced exactly by linear beam movement at constant power. However, when the beam changes direction or is



(a) Micrograph of the mask.



(b) Micrograph of the resist layer.



(c) Micrograph of the aluminum structure.

Figure 11 | Optical micrographs

switched off, a rounded edge results. The radius of this edge can

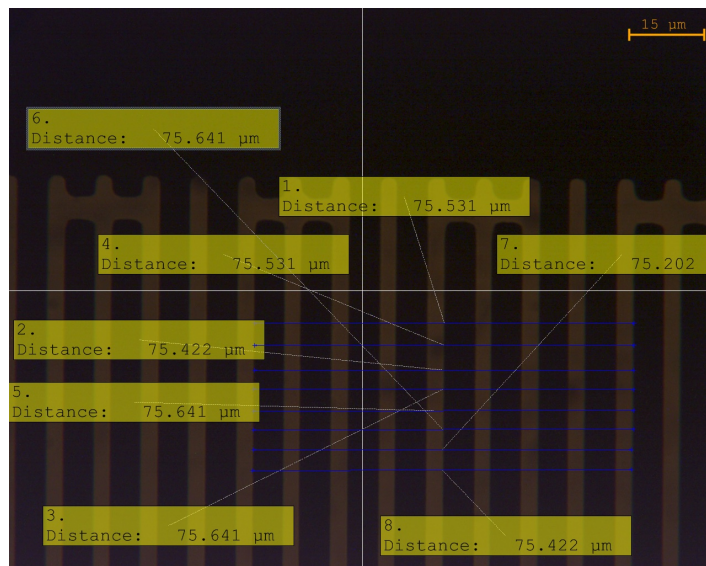


Figure 12 | Reference measurement to determine the measurement system accuracy.

be calculated from the intensity profile and the photoresist sensitivity. Subsequently, the same structure is measured on a wafer with a developed photoresist pattern and on the finished wafer using a reflected-light microscope. The measurement procedure is again performed at 100× magnification using the same software as with the mask. The measurements are shown in Fig. 11b and Fig. 11c. From the micrograph of the photoresist structure, it can be seen that, as with the mask, the finger structures appear noticeably wider than the gaps. In the finished aluminum structure, however, the widths of both the fingers and the gaps are relatively similar. The structures on both wafers exhibit rounded corners, as on the mask. Wet etching typically rounds sharp corners. In this case, however, the mask has only soft edges, which are transferred to the photoresist structure in the same way. Therefore, the rounding of the aluminum structure as a result of wet etching is rather unlikely.

Assessment of Measurement Accuracy To properly evaluate the measured values, a reference measurement was first performed to demonstrate the accuracy of the measurement system. This reference measurement is shown in Fig. 12. The 8-fold distance consisting of one finger width and one gap width was measured. This measurement was performed 8 times. The theoretically expected value is $2 \times \lambda_0 = 75.2 \mu\text{m}$. The values calculated by the software range from $75.202 \mu\text{m}$ to $75.641 \mu\text{m}$. Additionally, the 8 measurements yield only 4 different values. One can conclude that the second and third decimal places are not reliable. More importantly, the measured value fluctuates within an interval of approximately 400 nm. However, for each sample, only a single measurement of the finger widths was performed, making it difficult to interpret the measured values for our small structures. To make better statements about the measured values, a measurement series should be performed or, ideally, measurements should be taken at a higher magnification. Given the present data, it must be assumed that, in the worst case, the values could deviate by approximately 400 nm from the true value. This statement is supported by the fact that repeated measurements of the finger widths on all samples consistently yielded values differing by a few hundred nanometers.

Interpretation of Measured Values First, the measured values on the mask and the photoresist structure are compared. Finger

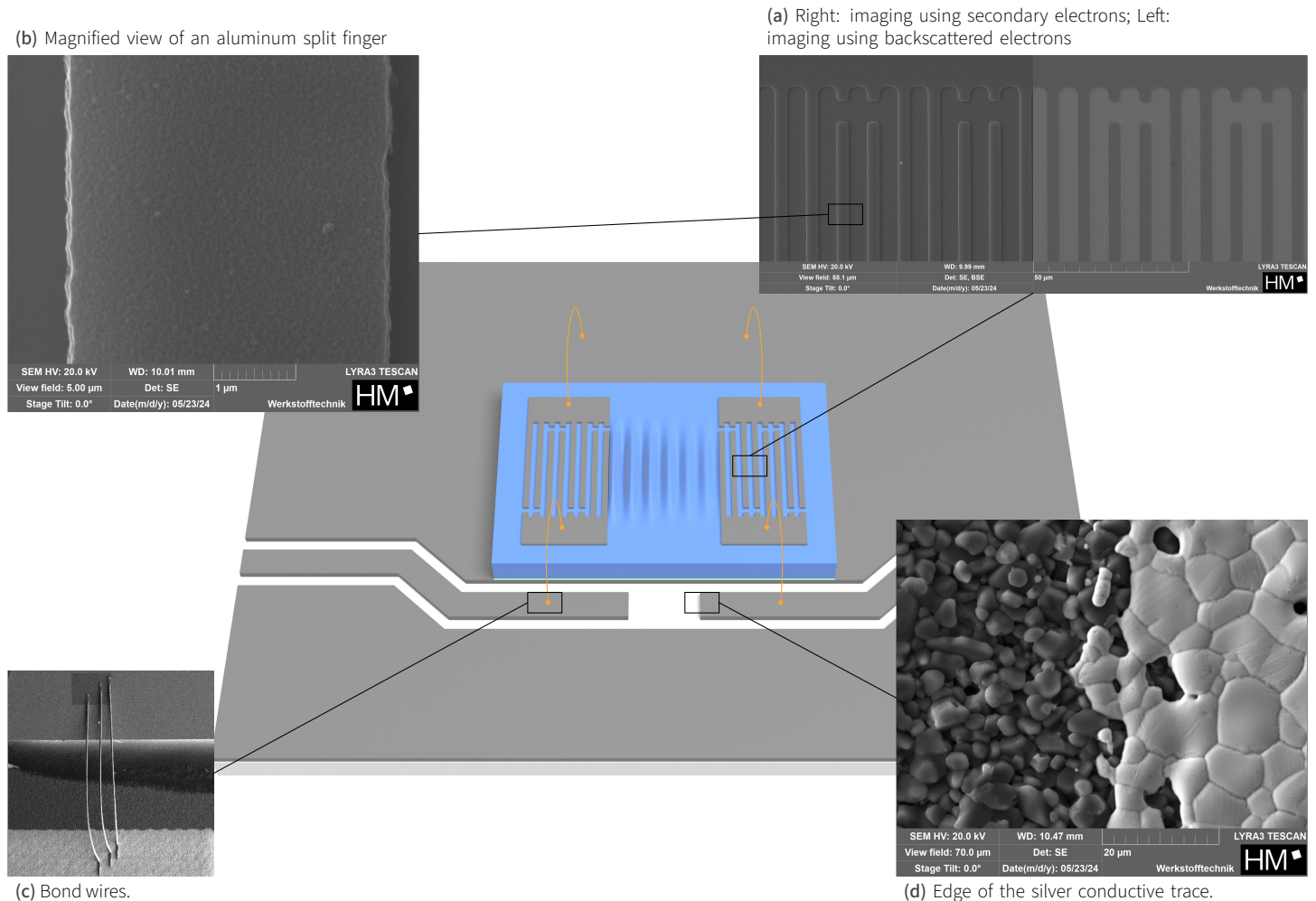


Figure 13 | SAW filter on the ceramic substrate. The SEM images are assigned to locations on the sample.

widths of $5.932\ \mu\text{m}$ and $5.600\ \mu\text{m}$ were measured, respectively, and gaps of $2.932\ \mu\text{m}$ and $3.644\ \mu\text{m}$, respectively (see Figs. 11a and 11b). Within the measurement accuracy, it can be said that the dimensions of both structures are approximately the same. However, it can be seen that the value for the finger width on the photoresist is smaller, and therefore the gap width is larger. Although this discrepancy is difficult to quantify, it can be expected when considering that a photoresist layer thickness of approximately $1850\ \text{nm}$ was measured. Despite the fact that the mask and photoresist were brought into contact during exposure (contact lithography), it can be assumed that UV light with a wavelength in the range of $300\text{--}500\ \text{nm}$ exhibits very small, but possibly not negligible, diffraction effects. Additionally, it is possible that the light rays do not strike the resist surface exactly parallel. However, the measured structure is located near the center of the wafer, so this effect should be smaller. Comparing the measured values on the finished wafer with those of the photoresist structure reveals significantly larger differences. For the finger width and gap on the aluminum structure, measurements of $4.979\ \mu\text{m}$ and $4.537\ \mu\text{m}$ were obtained, respectively (see Fig. 11c). Due to wet etching of the aluminum, the finger width of the aluminum structure was expected to shrink by at least $200\ \text{nm}$ on all sides relative to the photoresist structure. The measured value should therefore be at least $400\ \text{nm}$ smaller. However, since we etched by sight, the value should be greater than $400\ \text{nm}$ smaller. Within the measurement accuracy, this expectation is confirmed. For the SAW filter to function at the expected center frequency, the finger width actually plays no role, as long as the edges are separated

by $\lambda_0/4$, the filter will operate as planned. This was verified by measuring this distance on all samples. To improve measurement accuracy, 4 times this distance (λ_0) was measured, yielding values of $37.546\ \mu\text{m}$, $37.511\ \mu\text{m}$, and $37.689\ \mu\text{m}$. The expected value is $37.6\ \mu\text{m}$, so it can be said that the filter should meet the expected center frequency with good accuracy. It is apparent that after all process steps, the sum of the measured distances (finger width plus gap width) should remain the same. When one of the two quantities becomes smaller by a certain amount, the other increases by the same amount.

3.4 SCANNING ELECTRON MICROSCOPY

Sample Preparation First, liquid silver conductive adhesive is applied to the sample holder with a brush, and then the ceramic carrier with the SAW filter is pressed onto the holder. Alternatively, a double-sided carbon tape can be used. The sides of the ceramic carrier are also coated with the adhesive, since an electrically conductive connection between the sample surface and the sample holder must exist.

Sputtering the Surface In this experiment, the surface of the SAW sample, which has been conductively attached to the SEM sample holder, is sputtered with platinum. Alternatively, gold could be used. The sample is treated in a sputter coater using the so-called magnetron-sputter method with argon as the sputter gas. The sputter coater consists of a cylindrical chamber with a

cover, beneath which the platinum target is located. The sample is positioned on a holder in the lower part of the chamber. Before the sputtering process can begin, the interior of the chamber must be evacuated. When the target pressure is reached, argon plasma is generated within the chamber. This plasma is accelerated toward the platinum target, causing platinum atoms to be ejected. These atoms fall onto the sample surface under the influence of gravity. The chamber contains a sensor that measures the deposited layer thickness. In our case, the sputtering process takes approximately 40 seconds, achieving a layer thickness of approximately 0.8 nm.

SEM Analysis The prepared sample is placed in the specimen chamber of the SEM. Once sufficient vacuum is achieved within the chamber, various regions on the sample surface are imaged (see Fig. 13). To obtain images with sufficiently high resolution, care must be taken to focus the image at higher magnification. One image artifact that can occur is astigmatism, which is detected when the image moves back and forth laterally during focusing. This effect can be corrected using so-called stigmators within the SEM—8-fold coils. The detection of the chemical composition of structures on the surface is accomplished using an energy-dispersive X-ray (EDX) detector within the specimen chamber.

3.5 SUMMARY OF MEASUREMENT RESULTS

The measurement results are summarized in Table 4.

Measured Quantity	Value with Unit
Photoresist layer thickness	ca. 1850 nm
Al-IDT structure layer thickness	between 200 nm and 220 nm
Finger width and spacing ¹ on mask	5.9(4) μm and 3.0(4) μm
on photoresist	5.6(4) μm and 3.6(4) μm
of Al structure	4.5(4) μm and 5.0(4) μm
Distance corresponding to λ_0 ¹ on mask	37.5(4) μm
on photoresist	37.5(4) μm
of Al structure	37.7(4) μm

¹Measured structure: “C31”, $\lambda_0 = 37.6\mu\text{m}$

Table 4 | Summary of measured values.

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