METALSFOCUS

THE OUTLOOK FOR NEW ELECTRICAL & ELECTRONIC USES OF SILVER

PREPARED FOR

THE SILVER INSTITUTE

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CONTENTS

1. Executive Summary

1.1 Introduction

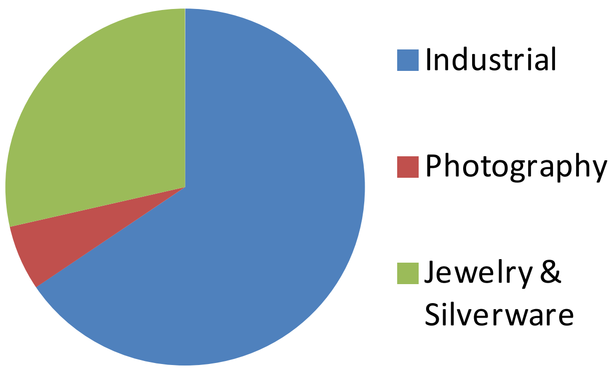
Silver lies at the heart of the electrical and electronics value chain, acting as an enabler for a vast range of applications. It is, therefore, almost impossible to envisage the future of such applications without the white metal. It has exceptional conductivity and reflectivity among all the chemical elements, making it the obvious choice for many electrical and electronics items, while its relative affordability can make it an attractive alternative compared with other precious metals.

Historically, industrial demand for silver has contributed the largest share of total offtake, averaging around 50% in 2013. Electrical and electronics applications, meanwhile, have accounted for the bulk of this demand. As such, it is no surprise that tracking developments within this category is of immense importance to the silver market as a whole.

The Silver Institute, in recognition of this fact, has commissioned Metals Focus to identify key growth areas within the electrical and electronics sphere. In Chapter 3 of this report, we focus on three specific applications, each of which have the potential to enjoy a strong growth trajectory. These are: **flexible electronics**; **light emitting diodes (LEDs)**; and **interposers**. Although they might not necessarily all be termed 'new' technologies, this is very much the case in the context of the silver market, as the use of silver in these applications is yet to reach widespread commercial use.

The volumes of silver demand on a per unit basis in the above applications, as published in the table on Page 4, might at first glance seem relatively modest. Although this may appear to be a challenging trend for silver offtake, it can in

Silver Fabrication Demand*, 2013



*excludes coins & bars; Source: Metals Focus fact be considered a positive development. Indeed, one reason why silver is set to have a significant role within each of the above new uses is because of the modest amounts of silver required on a per unit basis.

Although careful management of silver content is by no means new, technological developments have propelled this ability further, for example through the development of nanosilver or deposition techniques. Silver is thus available to market participants at a yet-more attractive price points, as well as occupying a lower share of overall costs. This is a key point in helping to secure the long-term future of the white metal in many of these applications, underpinned by its technical attributes.

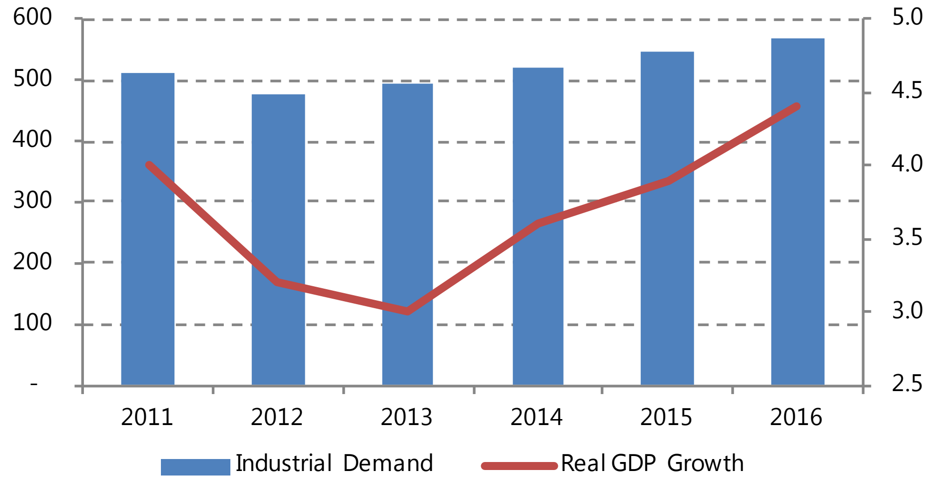
1.2 Industrial Demand Forecast

The purpose of this report is to focus on some new and exciting uses for silver in the industrial space and specifically in electrical and electronics. That said, it is also worth taking a step back to look at both the overall state of play for global industrial demand, together with our expectations for the coming years.

Last year, global silver industrial demand rose by around 4%. This may appear modest, but it hides a much stronger final six months in 2013 following a challenging first half. Importantly, the recovery has carried over into 2014 and, as such, we expect the global total this year to rise by 6%. A key driver will be the continued recovery in photovoltaics (PV), which experienced a difficult eighteen months or so through to mid-2013. However, a strong uptrend now appears underway, typified by a jump in Chinese silver powder imports. A range of other end-use sectors are also expected to contribute to this year's improved total, including the automotive and construction industries.

Looking further ahead, a period of uninterrupted growth looks set to develop. A key driver will be the continued improvement in world GDP growth, in part as the European economy establishes a more solid footing. However, two key areas of uncertainty concern the outlook for China and India. At this stage, neither

Outlook for Silver Industrial Demand



Source: Metals Focus, IMF, various

is expected to see a repeat of the growth levels achieved before the global financial crisis. Even so, world industrial demand for silver is still expected to outperform global GDP growth, with the former slated to rise by around 5% in both 2015 and 2016.

1.3 Outlook for New Electrical & Electronic Uses

Flexible Electronics

Flexible electronics represent the next generation of consumer electronics products. The term covers a wide range of innovative applications, with uses as diverse as: wearable electronics, including smart watches; wearable medical sensors; sensors to monitor large structures for stress (such as bridges, dams and skyscrapers); flexible solar cells (for tent roofs and boats for example); and, perhaps most importantly, flexible displays. It is therefore this last application that we have focused on in this report, as it represents the largest overarching category for potential growth in silver demand.

The main opportunity for silver comes in its use in the touch screen of flexible displays, whether in tablets, cell phones or e-readers. The market for such displays is expected to enjoy a strong growth trajectory, not only eventually replacing existing display products, but also forging new markets.

Light Emitting Diodes (LEDs)

From one perspective, LEDs might not be considered a new application. However, they are yet to reach their full potential in terms of market penetration. For silver, they also pose a relatively new frontier. Even though the white metal's role in LEDs has so far been relatively small, going forward this is very much likely to change.

Silver Consumption by End-Use in New Electrical & Electronic Applications

	Silver Consumption per Unit of Demand	Silver Consumption, 2014	Forecast Silver Consumption, 2018
Flexible Displays[1]	$10g/100m^2$	0.2 Moz <	1 - 2 Moz
LEDs[2]	Various	3 Moz* <	6 - 8 Moz*
Interposers[2]	Various	0.1 Moz <	5 - 10 Moz

* Includes Reflective layers, Adhesive layers, Bonding wire

Source: [1] rent-a-scientist GmbH and ras materials GmbH ; [2]Metals Focus

Silver has been found to play a vital role in a number of key areas in LEDs, notably in the reflective layer(s), adhesion layer and in bonding wire. Overall, LEDs are expected to show strong growth for the foreseeable future, driven primarily by a rapidly falling cost of LED production that will accelerate their presence into the mainstream. As such, the myriad of applications that LEDs can fulfill, from signage to data communications, will entrench silver's role in this promising growth area.

Interposers

Interposers are a new application that could hold considerable promise for future silver demand. These small appliances are part of semiconductor 'chips', which are used in almost every conceivable type of electronics device. They enable the 'stacking' of these chips, which leads to improved performance, smaller size and lower costs.

Traditionally, interposers have been made of silicon. However, the technological demands on next-generation semiconductor chips means that silicon is fast approaching its limit in terms of performance. Furthermore, it is a costly material. As a result, concerted efforts have been made to find an alternative solution, which appears to be glass. It is silver's compatibility with this material that could pave the way to a healthy future source of demand.

The technology that involves silver use is, however, in an early phase of development. It is, therefore, important to note that there are several competing technologies in the field, some of which do not involve the white metal, notably copper. That said, there is the potential for silver to take a notable share of the total interposer market, thus creating an entirely new category of offtake.

2. Overview & Outlook for Silver Industrial Demand

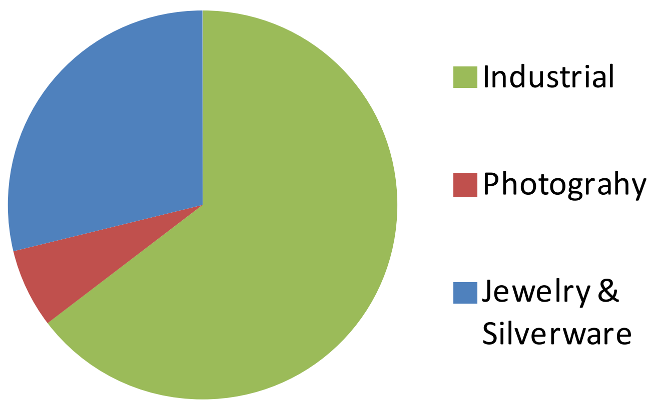
Introduction

Industrial fabrication is, by some margin, the largest source of silver demand, accounting for roughly half of the total in a typical year. Before the financial crisis, industrial offtake had enjoyed a period of strong growth, punctuated by the dot-com crash in 2000. Over this period, industrial output was underpinned by developments in new technology, booming consumer demand and the growing importance of the developing world, which played a pivotal role in driving silver industrial offtake.

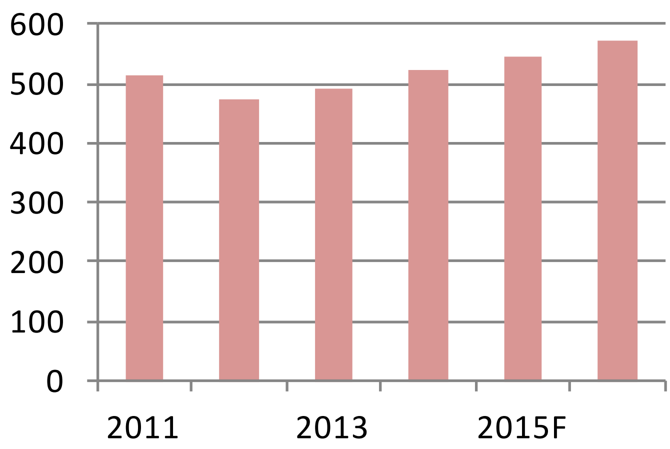
In recent years, however, industrial demand for silver has gone through a more difficult period. The 2009 global recession and subsequent sluggish economic recovery in the industrialized world impacted end-use demand in several key industrial sectors. Much of this decline can be attributed to falling sales of consumer electronics and the downturn in construction. Furthermore, high and volatile silver prices, especially silver's rally to $50/oz in 2011, led to efforts to target the silver content in some applications.

Last year, global silver industrial demand appears to have turned the corner, rising by around 4% y-o-y. This may appear relatively modest, but this reflects a poor first half followed by a more solid year-end. The upturn during late 2013 was due to improved demand across several end-use segments, as sentiment towards the global economy became more positive over the course of 2013. Furthermore, the weaker silver price means that thrifting has become far less of a threat to industrial demand, than was the case over 2011-2012.

Silver Demand in 2013, Moz



Silver Industrial Demand Forecast, Moz



Source: Metals Focus

Sectoral Review

Given that silver possesses the highest electrical conductivity of any element and the highest thermal conductivity of any metal, the use of the white metal in industrial offtake covers a wide range of applications.

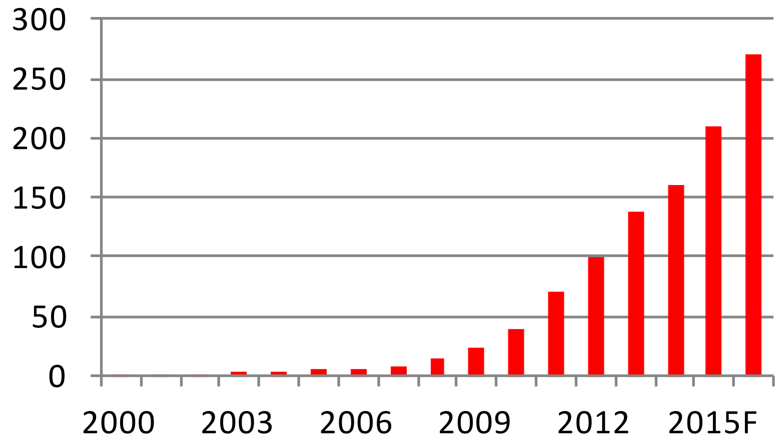
The electrical & electronics sector accounts for the largest slice of silver industrial demand. As such, it is the sharp rise in this sector that has contributed to the bulk of gains in silver industrial offtake. Key drivers behind the strength of electrical & electronics demand can be attributed to the tremendous rise in sales of several well established end-use segments, ranging from consumer electronics to automobiles.

One key area for silver use in this electrical & electronics sector worth highlighting is photovoltaics (PVs), which enjoyed significant growth from the mid-2000s through to late 2011. In sharp contrast, late 2011 through to early 2013 saw a marked downturn, following a rapid build-up in 2011 of both excess production capacity and inventories of finished cells, principally in China.

Increasing efforts to reduce silver loadings by the industry, following the spike in silver prices in 2011, led to further downward pressure on silver offtake. That said, PV demand started to improve in late 2013, following the trade settlement between EU/US and China and consolidations across the industry, with further support stemming from a significant slowdown in thrifting during 2013. Other common uses of silver in this electrical & electronics sector includes the use of multi-layer ceramic capacitors and the use in conductive adhesives.

Another important area of industrial demand is the use of silver in brazing alloys and solders. The key end-use sectors include the HVAC/R system (heating, ventilation, air-conditioning and refrigeration), plumbing and automobile production. Generally, the performance of silver demand tends to follow the trend in world GDP growth. It was therefore of little surprise that silver demand weakened as the financial crisis emerged. Equally, since that time, brazing

Global PV Installed Capacity, Gigawatts



Source: Various

offtake has recovered, chiefly thanks to China where industrial offtake has benefited from the government's massive stimulus package.

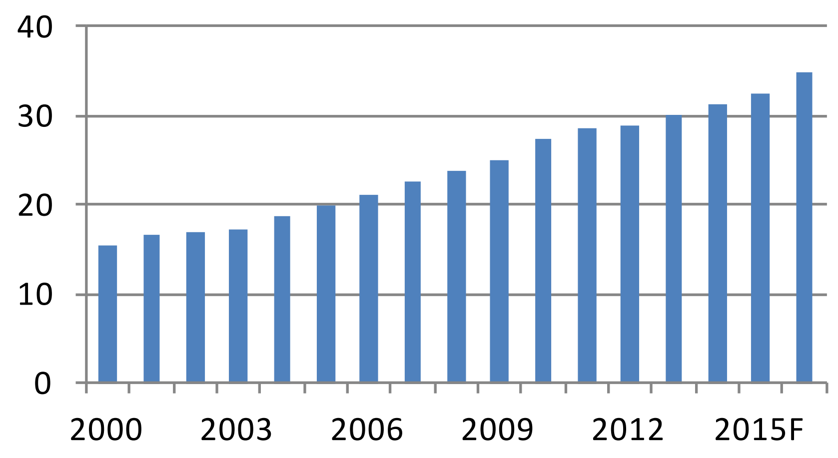
In terms of other silver industrial uses, an important area has been the ethylene oxide (EO) sector. Even though annual demand is relatively modest and the industry has not seen a tremendous upturn similar to that of PV, it has enjoyed near uninterrupted growth over the past 30-40 years. The rise can be explained for two reasons. To meet growing demand for a range of consumer and industrial products, newly installed EO plants are, on average, increasing in size. Second, the market has continued to see the introduction of new plants, especially in the Middle East and south and east Asia. Looking ahead, with the advent of shale gas, we could start to see the introduction of new plants in the US, which only a few years ago would have been considered unrealistic.

The last area to touch on concerns new uses. Because of silver's unique characteristics, it is hardly surprising that the market has witnessed the introduction of a raft of new uses, ranging from wood preservatives to biocides. Several of these have achieved commercial success, in terms of their ability to exploit silver's properties, with the medical sector a notably beneficiary. However, a common challenge has been the small level of silver offtake which has often been achieved on a per unit basis. As such, the impact on total silver demand of many new applications, has often been quite modest.

Regional Analysis

Moving away from a sectoral to a country or regional view, the industrialized world has historically dominated silver industrial offtake. In spite of the post-2009 recovery, silver industrial demand in advanced economies remained under pressure, as economic conditions, especially in the Eurozone, remained generally poor. However, growing signs emerged of improved demand, noticeably

Global EO Capacity, million tons



Source: PCI Xylenes & Polyesters

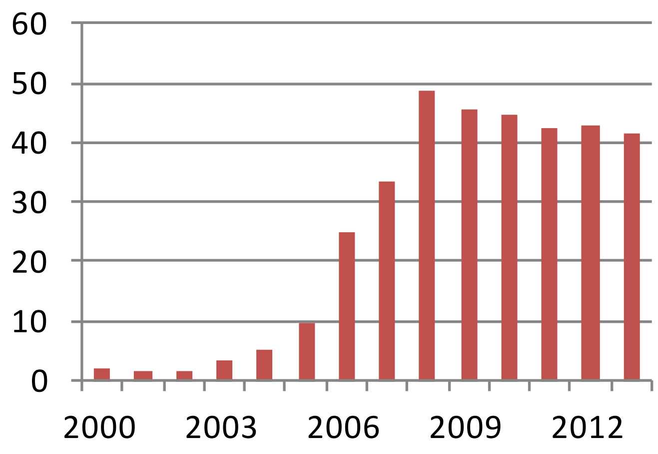
towards end-2013, with much of this momentum carrying through into 2014. The US has been one of the world's largest silver industrial fabricators. Over the past 10-15 years, even though US factories have been relocated to lower cost locations, primarily in Asia, US fabricators have retained many of their original supplier relationships, by "simply" exporting an increasing portion of their silver products (e.g. powder and flake) overseas. This has proved to be a highly successful strategy, which has seen the US retain its dominance in the silver industrial landscape.

Japan is another prominent silver industrial fabricator in the industrialized world. Domestically, silver offtake has endured a difficult period, as the country's industry production was hit by weak exports and at home and the earthquake and tsunami. Since then, demand has recovered strongly, driven largely by rising consumption of silver powder, the key starting point for the PV industry. Indeed, despite a difficult period for the PV sector, the last two years have seen Japanese manufacturers gain market share, highlighted by a rise in the country's silver powder exports to key industrial players. Elsewhere, silver demand in other industrialized countries in East Asia, namely South Korea and Taiwan, has also picked up noticeably, largely because of the rapid expansion in the consumer electronics industry.

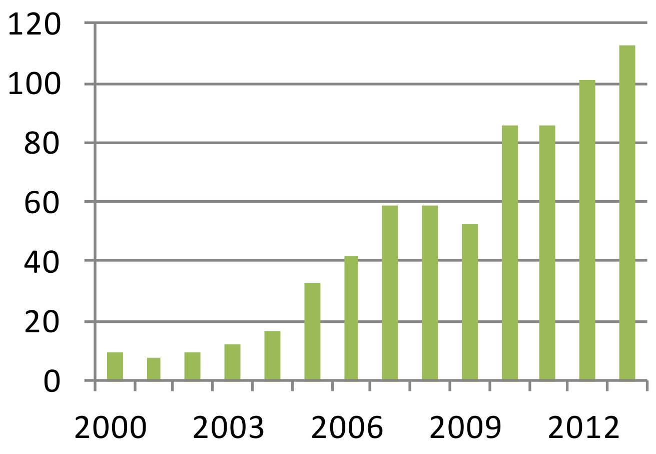
Finally, turning to the EU, given that the region's economy was hit hard by the recent economic and sovereign debt crises, it is not surprising that the decline in industrial offtake across much of the region has been particularly pronounced. That said, the trend across the EU has been quite mixed, with Germany enjoying a relatively steady performance, while more notable losses emerged in the debt-affected countries (albeit far smaller in terms of silver industrial offtake).

Turning to the emerging markets, China has been by far the dominant player. The country has enjoyed tremendous growth, benefiting from a robust economic backdrop. Specifically, rapid infrastructure developments and rising household incomes have boosted demand for silver-bearing products.

Chinese Silver Powder Imports, Moz



Japanese Silver Powder Exports, Moz



Source: GTIS

Meanwhile, the country has also benefited from the relocation of manufacturing capacities from mature economies, thanks to China's low manufacturing costs. Another key player is India, where demand has also posted solid growth. However, after improving noticeably in 2011, demand in the country posted successive losses over 2012-2013, due to a slowdown in Indian GDP growth, especially in light of delays in infrastructure projects.

Outlook

Looking ahead, industrial silver demand is expected to continue improving, with an average increase of at least 5% per annum slated for 2014-2016. This performance will largely be driven by healthy electrical and electronics offtake. The former includes a diverse range of applications spanning PV, the automotive sector and the construction industry (both private and government related).

Looking first at PV, following a difficult performance in 2012 and early 2013, the industry now appears to have emerged in strong health. Our understanding is that much of the finished PV cell inventory overhang that was in place has been depleted. Furthermore, global PV installations should achieve new record highs. That said, efforts remain to reduce silver loadings in PV cells, but crucially the rate of thrifting will be less than at its height in 2011. We therefore have to allow for the possibility that PV silver demand may surpass its previous peak (registered in 2011), perhaps as early as 2016-17.

In terms of other areas of electrical demand, namely the automotive and construction sectors, we also retain a bullish view. In particular, the auto industry offers a key example of a sector that might be considered mature, but where new silver demand is continually emerging, in terms of new applications, such as rear view sensors and lane guidance. Elsewhere, there are signs in some key markets of an improvement in construction and infrastructure spending, as well as in the housing sector (for example, in the US).

Given all of the above, it may seem that our forecast growth of 5% per annum is somewhat cautious. However, even though the economic recovery in western economies appears to be gathering momentum, there continues to be some uncertainty as to how much this is feeding through into the real economy. In addition, we have to remember that industrial silver offtake has already reached elevated levels, resulting in more modest growth rates going forward. Finally, over much of the 2000s, China and India enjoyed extraordinary economic growth, which may be difficult to repeat in the foreseeable future. Even allowing for these factors, for the 2014-16 timeframe, we still see silver industrial demand outpacing global GDP growth.

3. Outlook for New Uses

Summary

Familiar end-products, namely **displays**, **lighting** and **semiconductors** are given a new lease of life through technological developments, with silver playing a pivotal role in enabling and accelerating the development of new variants.

Despite their small size, silver nanowires are set to make a significant impression in the field of **flexible displays**, which make use of their conductivity and near-total transparency.

LEDs, meanwhile, are set to increasingly benefit from the white metal's reflectivity properties, as well as its compatibility with phosphor. Silver also features in the form of an adhesive layer and bonding wire.

Interposers form an integral part of semiconductor chips and so are used throughout the electrical & electronics industry. Historically, these were made of silicon. However, going forward, technological demands are likely to instead favor the use of glass. This in turn could pave the way for silver to be used across much of the interposer market.

Introduction

In this chapter, we introduce three key applications that are set to see growth in silver demand. These are: flexible electronics; LEDs; and interposers. All of these applications are at a relatively early stage of development, either technologically or commercially, with the potential for strong growth in terms of silver demand. Current demand for these applications is estimated at less than 4 Moz; by 2018, however, we could see offtake exceed 15 Moz.

3.1 Flexible Electronics

Flexible devices are an exciting development in the electronics sphere that is set to revolutionize the way in which we interact with technology. The term 'flexible electronics' covers a range of potential applications, with uses ranging from flexible displays (used in devices such as smart phones and tablets) to sensors (used in applications as diverse as medical devices and buildings). For the purpose of this report, we focus on the flexible display market because it is arguably closer to commercialization than sensors (which are also a far less homogeneous category), hence is more pertinent for our silver demand forecast period of the next four to five years.

Most use of silver in such applications tends to be in the form of nanosilver. Although there are several different types of nanosilver, it is most commonly defined as silver that has a particle size of 1-100 nanometers (nm) in diameter. The large surface area to volume ratio means that nanosilver is highly effective at lower concentrations than would be possible with conventional silver, thus offering greater cost efficiencies.

Silver nanowire, for example, is a form of nanosilver. Silver nanowires are ideally a few tens of nanometers in diameter, a few micrometers long and are wire-shaped, in contrast to silver nanoparticles, which are generally spherical. Spherical silver nanoparticles generally achieve less electrical conductivity than silver nanowires, as their round shape means their potential points of contact with each other are far more limited compared to nanowires.

Flexible Displays

Flexible displays (FDs) are made of a substrate using pliable materials, such as plastics, in contrast to the inflexible glass-based displays that dominate the market today. The myriad possibilities in terms of end-uses mean that FDs are set to take significant share from the inflexible displays of today that we are already familiar with, as well as encroaching on applications that still use ordinary paper (such as adverts on billboards), matching the latter's pliancy while improving on its robustness and offering the functionality of LCD devices.

Flexible Display Screen

Source: rent-a-scientist GmbH and ras materials GmbH (RAS)
*RAS is a notable research and technology provider, that develops new processes and products across a range of disciplines and is renowned for its research into nanosilver.

Although FDs have been in development for a number of years, it is only now that they are approaching technological maturity. As such, the time to market is rapidly decreasing and we expect them to become commercially widespread well within the next five years, from a currently limited base.

Silver in the Transparent Conductive Film

The role of silver in FDs, meanwhile, lies in its use as an electrode within the transparent conductive film (TCF) layers. This is an essential component of touch screens and makes best use of silver's exceptional conductivity.

In touch screen technology, two layers of TCFs are separated by a small gap. When a screen is pressed in a particular place, the top layer touches the bottom layer, thereby closing an electric circuit to create a voltage. The coordinates of the touch are then interpreted to carry out the requested command. At present, the transparent electrode in most touch screens is made from indium tin oxide (ITO), which forms a solid, transparent layer in between the TCFs.

Advantages of Silver Nanowire

In terms of flexible electronics, however, ITO faces some critical drawbacks. First among these is the fact that it is a brittle, fragile material, which makes it inappropriate for next-generation flexible displays, as these will curve to a steeper degree than is possible for ITO. The use of silver nanowires, however, means that the TCF layer can be as flexible as that of the substrate layer, while the scale of the silver used means that there is no compromise in terms of transparency. Indeed, 95% transparency has already been achieved by some industry players.

Second, the way in which ITO is commonly applied (using the vacuum deposition process) is costly, difficult and results in significant levels of wasted material. Furthermore, the equipment is expensive and difficult to maintain. Silver nanowires, by contrast, can be produced in a comparatively straightforward way using a wet chemical process, which is then applied in a liquid formula. Traditional manufacturing methods for printing electronics devices, such as roll-to-roll processing, can also be used. This is a significant advantage over graphene (an immensely conductive material composed of carbon), for example, where complicated, time-consuming and expensive deposition techniques are necessary.

Third, over half of indium production is concentrated in China. It is produced primarily as a by-product of zinc and tin mining. Silver mine supply, by contrast, is not dominated to the same degree by any one region. The risk of supply constraints and its impact on silver prices, therefore, is far less relevant than is the case for indium.

It is worth noting, however, that there are several alternative technologies to silver nanowires in terms of flexible electronics. These include concerted research into transparent conductive oxides (TCOs) such as zinc oxide and

Focus Box: The Journey of Silver, from Stope to Screen

Elemental Silver (four 9s)

↓

Silver Nitrate (Powder)

↓

Silver Nanowires

↓

Wet Chemical Formulation with Silver Nanowires

↓

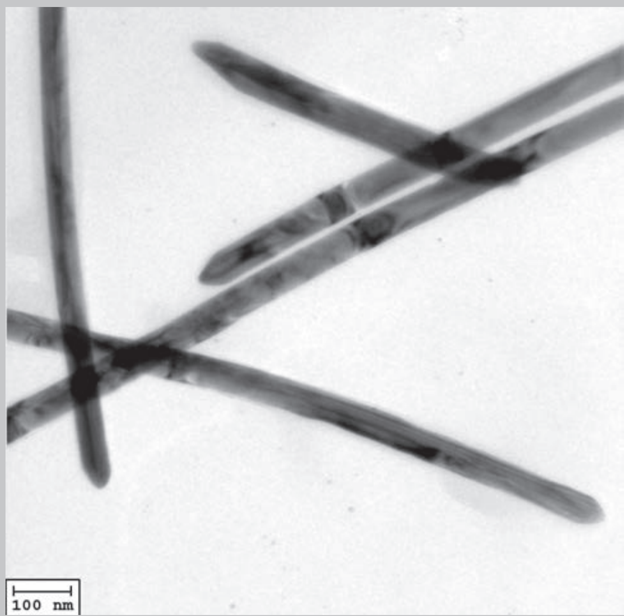
Ready-to-use coating, applied through roll-to-roll or other coating method

↓

Flexible Display

Above: The process of making silver nanowires for use in flexible displays

The story of silver nanowire starts in the same place that most silver originates from, namely a mine. Silver of four 9s purity is dissolved in nitric acid to form silver nitrate ($AgNO_3$), which takes the form of a white powder. This is the starting point to perform a chemical synthesis of silver nanowires, such as the ECOS™ process developed by rent-a-scientist GmbH. The nanowires then take the form of a wet chemical formula, which is a ready-to-use coating that can be easily processed in roll-to-roll facilities (although other coating technologies, such as slot dye coating and curtain coating, can also be used) to create brilliantly conductive display surfaces*.



Above: Image of silver nanowires, formed by chemical synthesis for use in display surfaces

Source: rent-a-scientist GmbH and ras materials GmbH

*Our thanks to rent-a-scientist GmbH and ras materials GmbH for kindly providing the above information.

graphene (despite its current costliness), as well as combinations of nanosilver with other materials. That said, none of these possible alternatives are at the same advanced stage of commercialization as silver nanowire.

Forecast Silver Demand

Given the advantages listed above, we believe that silver nanowires are in a strong position to become the technology to dominate the TCF market in flexible displays. By 2017, it is estimated that there will some 100 million square meters of transparent conductive surfaces on the market, well over double the current market size. This includes both flexible and inflexible displays, across all devices (including smartphones, tablets, all-in-one PCs and e-readers). Although the share of flexible devices will still be relatively contained at less than 20% of the total display market in 2017, this nonetheless represents an entirely new source of demand for silver. In terms of silver nanowire, there is an average loading of 10g of silver per 100sq meters. This should, therefore, result in demand approaching 0.5 Moz by 2017, with strong gains thereafter.

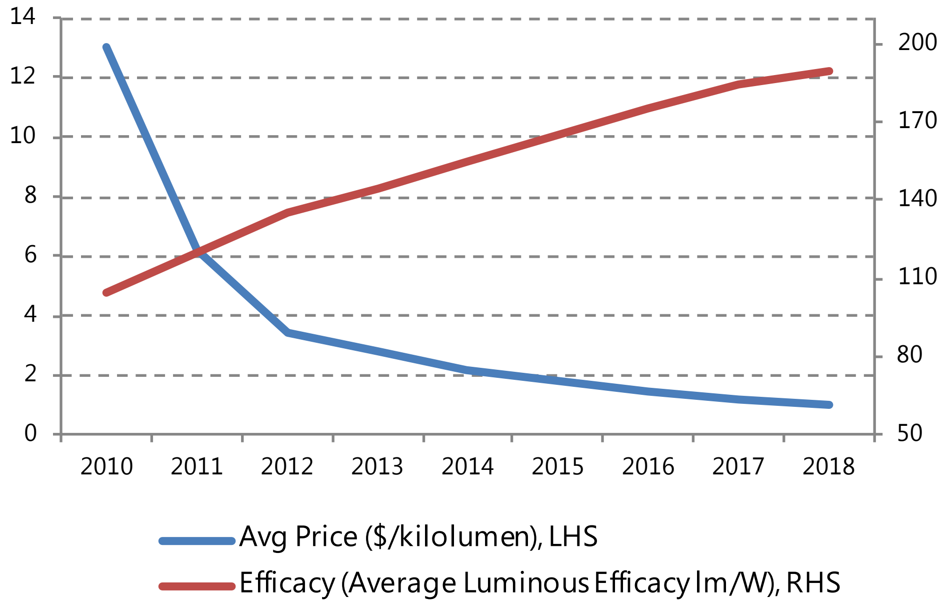
While this figure may sound modest, this is crucial in making silver economically viable to use on such a large scale. Furthermore, growth is set to soar, as we expect FDs to not only displace a significant proportion of the inflexible display industry, but also to create new markets for as-yet undeveloped products.

3.2 Light Emitting Diodes (LEDs)

A Light Emitting Diode (LED) is a semiconductor device that produces a narrow spectrum of light when a forward current passes through a diode (see page 17 for an explanation of silver's role in this application). LEDs have a myriad number of uses, including general household lighting, signage, automotive headlamps, camera flashes and backlighting display devices.

Some of the benefits of LED lighting compared to traditional light sources are: greater energy efficiency; better longevity; they are far more robust than glass bulbs as they are solid components; they produce significantly more light per watt than incandescent bulbs; they can emit intended colors without the use of filters (white light, for example, is achieved by using a blue LED combined with phosphor); no mercury or other toxins are used; they light up extremely quickly, vital in communications devices; they can produce a well-defined beam; and, finally, they emit no ultraviolet (UV) radiation.

LED Cost versus Efficacy



Source: Metals Focus

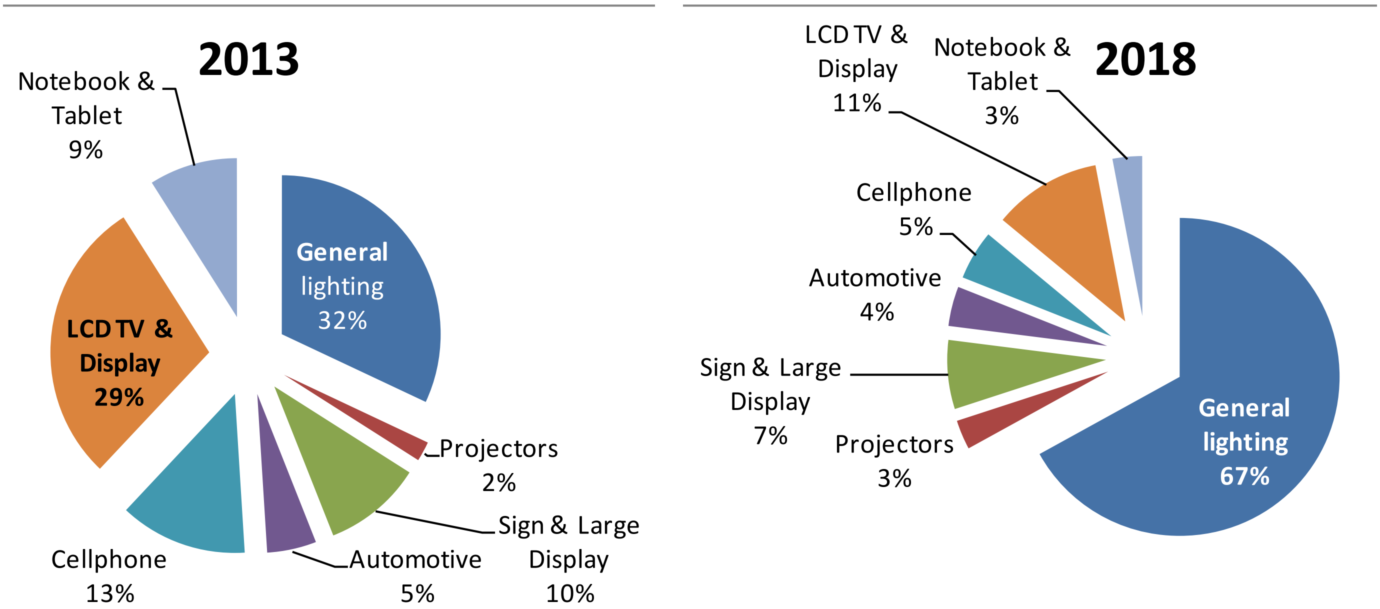
In 2013, LED penetration achieved almost 20% of the total lighting market. This year, we expect it to reach 30%. The key metric, by which to measure LED viability, is luminaire efficacy. This refers to the amount of electrical power required to produce a certain intensity of light, measured in lumens per watt. According to industry technology roadmaps, the average luminaire efficacy of commercial high brightness white LEDs will approach 200 lumens per watt (lm/W) by 2018, up from around 150 lm/W this year. Crucially, as efficacy increases, the unit price per bulb is expected to drop to around $1/kilolumen (klm) by 2018, down from around $3/klm last year.

There are, therefore, still significant cost reductions and efficiency gains to be made before we can expect to see mass adoption of LED lighting. This expected increase in efficacy and lower costs will be due, in no small part, to the use of silver. Given the white metal's excellent performance versus cost, it is widely accepted that silver is the ideal material to accelerate LEDs efficiency gains through a number of different avenues.

Outlook for LEDs

Looking ahead, we expect LED demand to maintain its healthy upward trend. Indeed, according to the consultancy NPD Display Search, overall LED chip demand (measured by the standard 500 x 500 micron chip size), is forecast to surge from 17 billion units in 2012 to 61 billion units in 2014. This rise comes despite a forecast decline in demand for backlight chips, for TVs and other displays, which has been driven by a combination of falling LED-backlit LCD TV sales and efficiency increases that have resulted in fewer chips used per backlight.

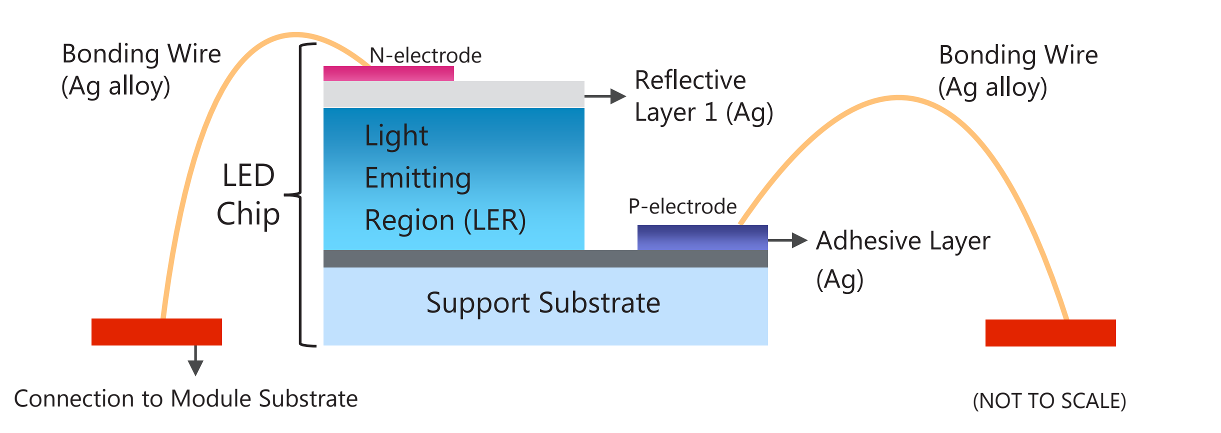
Packaged LED Chip Consumption, 2013 vs 2018



Source: Metals Focus

Focus Box: Understanding LEDs

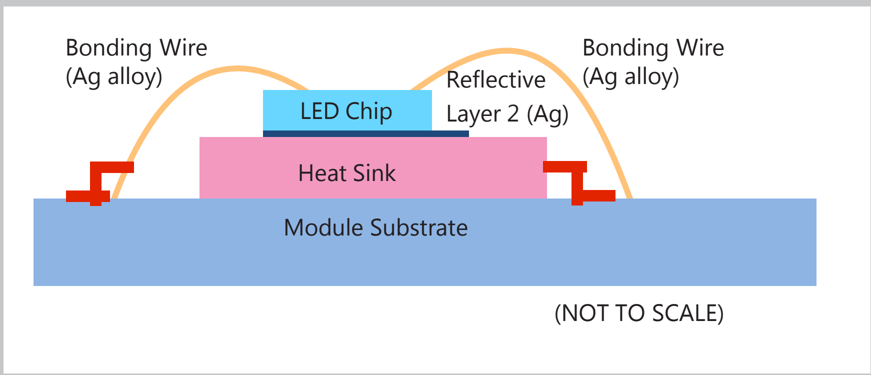
Structure of a Typical LED



Source: Metals Focus

Above: This illustration shows a simplified image of a typical LED chip. The LER is the semiconductor material, composed of alternate layers of N-type material (connected by the N-electrode) and P-type material (connected by the P-electrode). The N-type material is negatively charged due to the fact that it carries negative electrons. The P-type material, in contrast, has extra positively charged holes. When an electric current is passed through the device, via the silver alloy **Bonding Wire,** charge flows from the N-electrode to the P-electrode. This causes the extra electrons from the N-type material to fill the holes in the P-type material and this process releases photons (light) from the light emitting region. This light output is maximized by the presence of **Reflective Layer 1**, composed of silver. Without this layer, light tends to reflect back into the LER. The **Adhesion Layer**, meanwhile, makes use of silver's conductivity and bonds the LER to the Support Substrate. This substrate in turn connects the LED to the heat sink (shown below) and can be made from materials such as sapphire, silicon and silicon carbide.

An LED Module



Source: Metals Focus

Above: This shows the LED module in total, that is, the Heat Sink and Module Substrate layer as well as the LED chip. A heat sink is necessary to dissipate the large amount of heat that is generated when a current is passed through the LED. If the heat is not removed, the LED will function less efficiently, eventually causing complete malfunction. The heat sink has a large surface area to maximize heat transfer. **Reflective Layer 2**, comprised of silver, is shown in between the LED chip and the heat sink; this acts to reflect light away from the module in order to optimize output. The addition of this second reflective layer is a relatively new innovation, but is expected to gain traction as a way to improve efficiency. The LED is connected to the module substrate below the heat sink via silver alloy bonding wire.

As such, much of the growth will come from the general lighting sector (as illustrated below), driven not only by technological improvements that will lower the cost of LEDs, but also because of lighting energy legislation which is set to encourage LED adoption in many major energy markets.

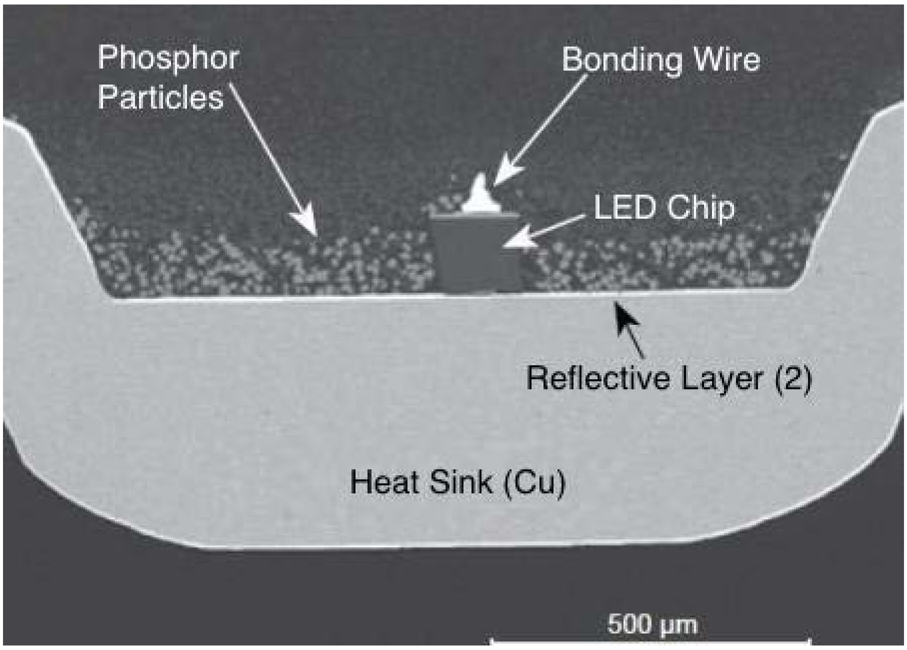
Silver in LEDs

The basic configuration of an LED chip is illustrated in the above Focus Box. The backside of the light emitting region (LER) is coated with a reflective layer, which reflects light outward. An adhesive layer then connects the LER to the support substrate. These combined components are known as the LED chip.

The LED chip is then mounted onto a heat sink (necessary to dissipate the high volume of localized heat that is generated when the LED is operated), which is in turn mounted onto a second substrate layer. The LED chip, combined with the heat sink and second substrate layer are known collectively as the LED module.

A second reflective layer can be applied in between the heat sink and LED chip, in order to further enhance light output. The heat sink, meanwhile, is mounted

Cross-section of an LED Module



Source: Evans Analytical Group, Materials Characterization Techniques for Advanced LED Analysis 2013

Above: This image shows the LED module in whole, with the LED chip mounted on the heat sink (made from copper, Cu, in the image above, although aluminum is also used). The large surface area of the heat sink is apparent here. Neither Reflective Layer 1, nor the Adhesion Layer, which both lie within the LED chip, (illustrated on the previous page) are visible at this scale, although we can see **Reflective Layer 2**. This layer performs the same function as Reflective Layer 1, namely reflecting light outwards. The cross section of the silver alloy **bonding wire** is also visible. As well as being an excellent conductor, silver alloy wire is necessary due to the presence of phosphor, which would erode copper bonding wire. Phosphor is crucial as it is responsible for determining the color of light emitted.

on a second substrate, that connects the LED chip to an outside circuit, much in the same manner as a computer's microprocessor is mounted into a package that has pins that connect it to a circuit board.

Silver can be found in both of the reflective layers and the adhesive layer. In addition, it can also be used in the bonding wire that serves to connect the LED chip to the module substrate and external electrical circuits, as shown above. According to our estimates, total silver demand used in LED applications fell short of 3 Moz last year. Over the next four to five years, however, this figure could more than double, to 6-8 Moz, in line with gains in LED demand. We address each of the ways in which silver features in LEDs in greater detail below.

Reflective Layer(s)

As also illustrated above (on page 16), the LER is coated with a reflective layer. This layer reflects the light that is generated when a current is passed through the LED. As silver offers excellent reflective properties across the visible and near infra-red light spectrum, it is the ideal material for this purpose, improving efficiency in terms of both performance and cost.

Accordingly, the white metal is already used as the reflective layer in the majority of LEDs that are available today. It is applied mainly through evaporation or sputtering, to enable good thickness control. As the thickness of the reflective layer is one to two microns, we do not expect current silver consumption in this use to exceed more than 1 Moz. That said, this volume applies to that used in Reflective Layer 1 only (that is, on top of the LER). This is due to the fact that the use of a second reflective layer (Reflective Layer 2), in between the LED and the heat sink, has been a relatively recent technological innovation, developed in order to further enhance light output. The addition of this layer has been shown to increase efficiency by up to 5%, which although it sounds modest, will lead to notable combined gains.

In terms of the forecast, therefore, we expect to see strong growth, with silver demand reaching in excess of 2 Moz within the next five years. This comes in line with the expansion of the LED market, underpinned by gradual gains from increased uptake of silver in the second reflective layer.

Adhesive Layer

The second area within the LED to use silver is the adhesive layer, as shown (see the Focus Box on page 16). The LED device is mounted on a substrate base (substrate materials range from stainless steel to anodized aluminum to high-performance ceramics such as aluminum oxide and aluminum nitrides). Traditionally, gold-based conductors (gold-tin, AuSn) have been used to connect the LED to the substrate, due to the stability and reliability offered by the yellow metal. Intense cost pressures combined with improvements in metalization technology, however, have meant that silver has become more prevalent as the interconnect material.

Silver can be been applied for this function in a number of ways, including vacuum deposition, thick film printing and plating. More recently, however, the industry has been moving towards the use of nanosilver powders, although this technology is still at the developmental stage. This has proved competitive both in terms of cost (compared to both AuSn and silver paste) and performance, offering not only better adhesion but also reflectivity, thus enhancing the reflectivity provided by the reflective layers.

As the use of silver powder has not yet, however, reached commercialization, our estimate for current demand is modest at less than 0. 5 Moz per year. It is, however, expected to reach the wider market in the near-term. Thereafter, we expect to see strong year-on-year gains which may total some 1-2 Moz within the next five years.

Bonding wire

Bonding wire is the infrastructure that connects the LED chip to an outside circuit, acting as 'packaging'. Conventionally, gold has been used in semiconductor packaging. The high cost of the yellow metal has, however, driven widespread substitution into other materials, including copper, palladium-coated copper, silver and silver alloys.

The latter, commonly silver-copper alloys, has proved a popular material to migrate to, given that it costs some 80% less than gold wire, while being competitive in terms of performance. In addition, it has proved to have better bonding workability, reliability and durability of electron migration than competing materials. Furthermore, the brightness of LEDs bonded with silver alloy wire is higher than those that have been bonded with gold wire, due to the superior reflectivity of silver. Another key reason for using a silver alloy is due to the presence of phosphor, found in most LED devices (phosphor is used to determine the color of light emitted and is essential to achieve 'white' light). Phosphor does not react with silver (or its alloys), but causes base metals such as copper to erode and thus malfunction.

Last year, the market size of silver alloy bonding wire in the semiconductor and LED industry combined reached some 60 million meters, resulting in around 1 Moz of silver demand. This is set to soar to approximately 180 million meters in 2016, before climbing further to around 240 million meters by 2018, equating to around 4 Moz of silver demand.

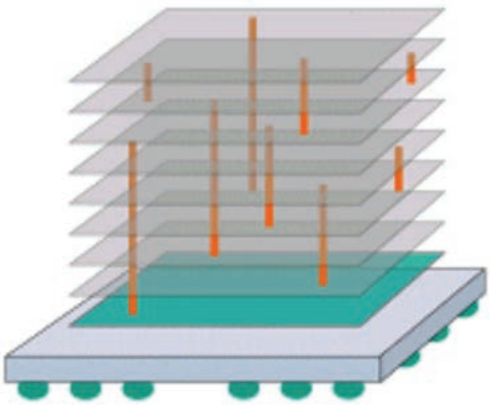
3.3 Interposers

Interposers are an integral part of enabling the next generation of semiconductor devices. Semiconductor chips themselves are integral to electronic devices, in both the consumer and industrial sectors. They are thus an ever-present, if unseen, part of our daily lives. Computers, medical devices and automotives to name but a few end-uses would be unthinkable as we know them without these tiny yet powerful products. The role of silver lies in facilitating the next stage of evolution in these essential devices. The largest drivers today in the advancement of semiconductor fabrication and packaging technology are increased performance, smaller size, and reduced cost. These key forces propel innovation along the entire value chain, including chip makers, materials suppliers and packaging service providers.

One trend in packaging that seeks to achieve these goals is that of stacking chips, both vertically and horizontally. Stacking multiple chips saves space and increases functionality, by reducing the 'footprint' of the chip and enabling a variety of chips to be integrated into a single circuit (see below). Furthermore, stacking means that power consumption is kept lower than possible in equivalent separate circuits. Stacking can also mean faster operation, due to the use of shorter, vertical wires, rather than lengthy edge-wiring.

This type of circuit is called a Three-Dimensional Integrated Circuit (3D IC), or a '3D package'. A variety of semiconductor chips with different functions, for example memory, CMOS (complementary metal oxide semiconductor) image sensors (used in digital cameras and other imaging devices) and MEMS (microelectromechanical systems, used in applications ranging from biomedical sensors to communications) can thus be integrated into a single package.
This stacking, meanwhile, is enabled by interposers. An interposer is an electrical interface that connects multiple connections. It is therefore instrumental in

Interposer Layers



Source: Yole Développement

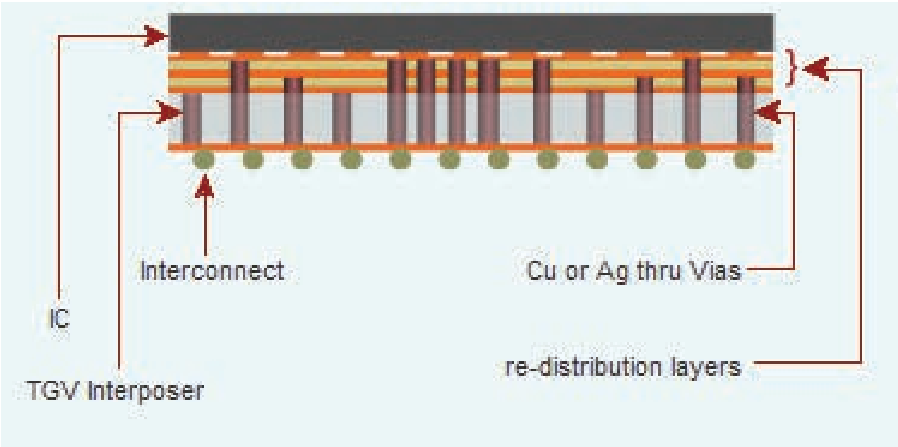
The above illustration shows the layers of interposers connected by the through-glass vias. The vias are filled with the conductive material, silver or copper. The small footprint of the device is apparent, achieved by vertically stacking the interposers. With a high count of stacked interposers, one can redistribute a dense array of I/Os from multiple IC chips. The multiple ICs would otherwise be connected to a circuit board in a planar manner (in other words, lying side-by-side on one plane, rather than on top of each other), thus wasting valuable circuit board real estate and not allowing for the size requirements of the end product, such as smartphones, smart watches or implantable medical devices.

ensuring that powerful multifunctional devices take up the minimum amount of space possible, a particular constraint in many handheld devices.

Interposers can also, however, be useful in larger devices, as they can spread a connection over a wider pitch. The pitch is the distance between pins on a circuit board that link the IC to the power supply. This means that the same chip size used in a small handheld device, such a s smartphone, can also be used in a larger application, such as a keyboard, without the need to reduce the size of all other interconnecting components, thus reducing both costs and complexity. There are electrical interconnects in both the vertical plane of the interposer along with electrical interconnection in the horizontal plane, hence why it is called '3D' packaging.

Historically, silicon has been the material of choice in interposer technology and still dominates today's market. More recently, however, glass is being touted as a serious alternative in this area by 3D package designers. Although it is currently in a pilot stage of production, it nonetheless holds considerable potential as the material of choice in the future. As the semiconductor fabrication industry is known as one of the most aggressive for building year-on-year cost reductions into its designs glass has emerged as a serious candidate to replace silicon for interposers. One of the major drawbacks to silicon is its relatively high cost. Glass, meanwhile, can offer a comparative cost reduction of up to 50%. Not only are the material costs lower, but the production of glass is also cheaper for a number of other reasons: it can be

Layout of a through-glass via (TGV) Interposer



Source: Triton Microtechnologies

The above image shows a type of TGV (through-glass via) interposer. In this instance, the vias can be filled with either copper or silver, depending on the manufacturer's specifications. The vias can be seen to connect at the re-distribution layers (shown in orange and green) uniting all the layers to the final interconnect layer (represented by the green spheres at the bottom of the diagram). These attach the semiconductor chip, or Integrated Circuit (IC), to a circuit board.

As this graphic shows, on the side-view of the interposers we can only see one IC, at the top of the diagram. There could, however, be multiple ICs on the same layer, each with a different function. These would also be connected into the redistribution layers by the TGVs, with a different number of input/output (I/O) connections (and thus different numbers of TGVs). The function of the redistribution layers is to reroute I/Os from the various chips through the interposer, ultimately interconnecting with the outside world of the circuit board.

produced on a far larger scale; it can be manufactured to the required thinness whereas silicon must be ground down, thereby entailing an extra process and therefore expense; there are fewer losses through breakages as glass wafers have been found to be stronger than brittle silicon. Furthermore, electronic signals can travel faster and with less signal "loss" than with conventional silicon.

The significance for silver in interposers lies in its use in through-glass via (TGV) technology. The vias are precise holes through the interposers that are typically formed by some sort of subtractive processing, be it chemical removal of glass or by laser. The resultant vias are filled with a conductive material, typically silver or copper, in order to make the top to bottom electrical connection between chips and interposer(s). As is so often the case in electronics devices silver faces stiff competition from copper. Equally, though, it is often the case that silver either asserts its superiority over the base metal and dominates a particular technology (as in photovoltaics) or that silver and copper co-exist to satisfy different requirements within one umbrella application (such as brazing alloys).

There are two main factors that work in silver's favor. First, there is a portion of glass manufacturing that is incompatible with copper. The additives used in the composition of certain types of glass are unfavorable to copper, such that copper is effectively "barred" from use in those manufacturing foundries. Silver, by contrast, has no such issues, with the glass formulations used for interposers and is thus the only material that can be used with those types of glass.

Second, the technology behind using silver as the via fill material is considerably more advanced than is the case for copper. Silver takes the form of a thick film that is either printed or extruded into and throughout the via, in a process that is not dissimilar to the process used in laying down silver grid lines in solar cells, hence this method of manufacturing is well established. For some manufacturers, this makes silver a more attractive option than copper, as already existing modes of production can be used or adjusted, rather than necessitating fresh investment in manufacturing infrastructure. That said, it is nonetheless important to note that there are certain types of glass interposers that can house either silver or copper as the via fill material (as illustrated on page 20).

With regard to the volume of silver used, the current market size is estimated to be less than 0.5 Moz of silver, in recognition of the fact that this is an emerging technology that is still in a developmental stage of production. Although it is yet to be determined which metal technology will ultimately win, there is nonetheless a possibility that silver will come to occupy at least a healthy proportion of the total glass interposer market even if copper also finds favor. Accordingly, we forecast that by 2018, silver-based interposers will have reached commercial production and could in principal consume 5-10 Moz per annum (this assumes that copper is not widely used, something that is difficult to predict now, given that this technology is still being developed). Further gains thereafter could also occur as the technology becomes more widely entrenched, underpinned by strong growth in end-use demand.

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