Silicon photonics open access foundry services review for emerging technology

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ABSTRACT

This paper presents a summary review of some of the available foundry services offering Silicon Photonics, comparing the key technologies available to European technology innovators that drive the technology sector. The foundries providing these unique technologies include AMF, CEA Leti, CORNERSTONE, Global Foundries, ihp, imec, and LioniX International. The review will also show examples of Silicon Photonics in emerging application domains from selected foundries.

Keywords: Silicon photonics, Silicon-on-Insulator, Silicon Nitride, foundry, photonic integrated circuit, open-access

1. INTRODUCTION

Photonics Integrated Circuit (PIC) is the art of controlling the flow of light on a chip. When that chip is made of silicon, it is a Silicon Photonics chip. Silicon Photonics has moved from being a prominent research topic to not only quickly becoming the backbone of datacenters around the world, but it is also considered the driving game-changer in many emerging technologies. It has unique physical properties, it is relatively low cost, has high yield, with outstanding performance and capable of complex design. Its ability to integrate with lasers as well as electronics has made it the enabler for emerging markets such as AR/VR, biomedical, life sciences, Agro-Tech, and quantum to name a few.

There are several foundries that make their technology available to academia, research institutes, start-ups and SMEs. Among them are; AIM Photonics in the USA, AMF in Singapore, CEA Leti in France, CORNERSTONE in the UK, GlobalFoundries in the USA, ihp in Germany, imec in Belgium, Ligentec in Switzerland, LioniX international in the Netherlands, ST Microelectronics in France, TSMC in Taiwan, and VTT in Finland, to name a few of the world leading foundries. This paper will review the key silicon photonic technologies from a subset of these foundries, along with examples in emerging application domains, based on their availability to European academics, researchers and innovators [1].

A range of materials can be used to manufacture Silicon Photonics, and consequently, the resultant devices display different performance capabilities. These include Silicon on Insulator (SOI), Silicon Nitride (Si_3N_4), and Silicon Germanium based devices to name a few. The functionality of the variants is described in section 2 within the context of the different Silicon Photonic foundries.

In section three, the paper gives an overview summary of open access platforms, their benefits, and highlights some key European foundries that give innovators open access to their unique platform. This is followed by section four, where examples of emerging applications make use of Silicon Photonics to enable and drive their innovations. Finally, an overview of foundries is summarized in section five, highlighting their si-based platform, ideal wavelength range of operation, and typical or emerging applications that they enable.

2. SILICON PHOTONICS FOUNDRIES

2.1 AMF Advanced Micro-Foundry

A spin off from IME A*STAR, AMF, accessed through CMC Microsystems, have a Silicon-on-insulator platform that has 220nm top Si film, with 2000nm Buried OXide (BOX), high resistivity handle wafer (>750 ohm-cm), 193-nm deep UV lithography for waveguides, enabling features down to approximately 140nm. It makes use of two partial etches and one full etch of the top Silicon 6 implants for optical modulators (P++, P+, P, N++, N+, N) Germanium deposition and implanting for photodetectors. Two metal levels, no planarization, front side oxide etch to selectively expose waveguides, which can be used for sensing applications. This enables a range of applications such as modulators, detectors, waveguides (strip or ridge), gratings for fiber coupling, deep trench and nano-tapers for edge coupling, multiplexers (diffraction or arrayed waveguide) and filters (resonators, Bragg gratings), ring and disk resonators [1].

2.2 CEA Leti

300mm versatile Silicon-Si_3N_4 platform developed by CEA-Leti allows for miniaturization, power efficiency, cost reduction and scalability of photonic integrated circuits. The platform makes use of two thicknesses; 220nm Silicon and 310nm. The first has 300mm high uniformity SOI substrate with 220nm Si, metal heater, one-level metal interconnect, deep trench for edge coupler. The 310nm recipe leverages 300 mm SOI substrate with 310nm Si, Si_3N_4 layer, 2µm buried oxide, 6 implant levels for p-type and n-type for modulators and doped Si heaters, 3 silicon patterning steps for Si heights of 0, 65, 165 and 310 nm, Silicide modulator contacts, metal heater, and 2 metal layers. Both the 220 and 310nm allow for telecom, Datacom, 5G, quantum cryptography high performance computing, quantum computing, neuromorphic computing for AI, gas sensing, structural health monitoring and 3D sensing such as LIDAR. CEA Leti also has an ultralow loss Silicon Nitride platform based on a high quality LPCVD Si_3N_4 layer. This platform enables the fabrication and testing of high-confinement, ultralow-loss Silicon Nitride waveguides and resonators showing average attenuation coefficients as low as ∼3 dB/m across the S-, C-, and L bands for 1.6-µm-width × 800-nm-height dimensions, with intrinsic quality factors approaching ∼107 in the C band. It uses 800nm high quality LPCVD Si_3N_4 with a minimum feature size of 200nm, and deep trench edge couplers. It supports ground and space communication, quantum cryptography, quantum computing, bio-sensing, bio-microscopy and 3D sensing such as LIDAR [1]. Figure 1 shows a silicon photonics chip fabricated by CEA-Leti with both optical fiber assembly (East/West) and electrical wire bonding (North/South).

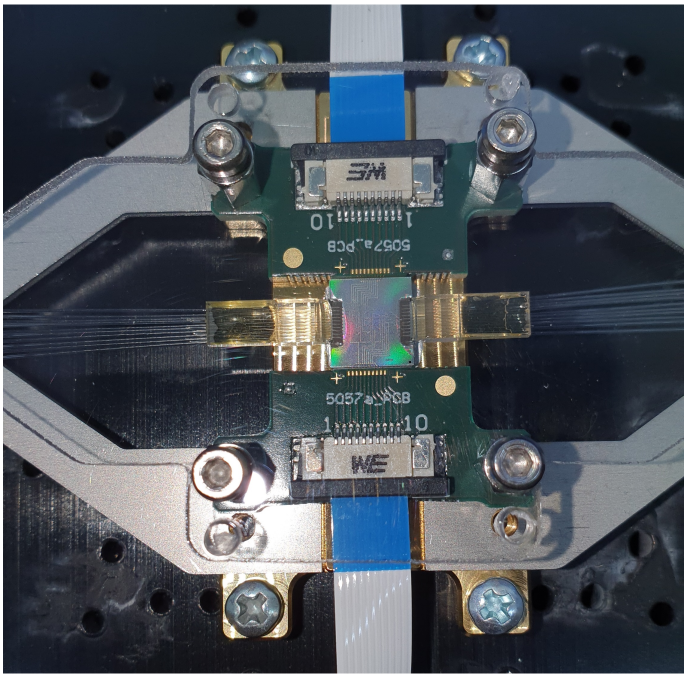


Figure 1. Silicon-photonics chip fabricated by CEA-Leti with both optical fiber assembly (East/West) and electrical wire bonding (North/South). The assembly was by PHIX. (Courtesy of Cailabs)

2.3 CORNERSTONE

CORNERSTONE, a collaboration between the Universities of Southampton and Glasgow, is a rapid prototyping foundry that provides users with access to scalable and non-scalable processes. CORNERSTONE achieves this through unique MPW services that have the capability to customize certain processes [2]. CORNERSTONE provide a variety of SOI recipes that suit different applications, for both passive and active devices. These SOI recipes vary based on the Si over-layer thickness: 220nm that is optimized for Datacom applications, 340nm suitable for quantum photonics applications, and 500nm for mid-IR (MIR) applications [2]. This technology platform is based on 248nm deep DUV projection lithography. This allows for feature sizes of 250nm and above. A key advantage of the CORNERSTONE method is that it allows for certain layers to be written using e-beam lithography, this in turn allows for feature sizes of 50nm, typically used for devices such as high efficiency grating couplers.

Another platform recently introduced to the CORNERSTONE portfolio is based on Silicon Nitride. A single-sided polished Si3N4 on Insulator wafer with a Crystalline Silicon substrate, thermal silica (SiO2) BOX layer with a thickness 3µm, LPCVD Silicon Nitride core layer thickness of 300nm +/- 30nm. This processes includes a full Silicon Nitride etch BOX layer 2µm +/- 200nm thick silicon dioxide top cladding layer with two metal layers for heater filaments, and contact pads [3]. Figure 2 is a schematic illustration of horizontal light grating couplers designed by Tyndall National Institute and fabricated using CORNERSTONE SOI platforms 220nm and 340nm, which is available through open access design rules [2].

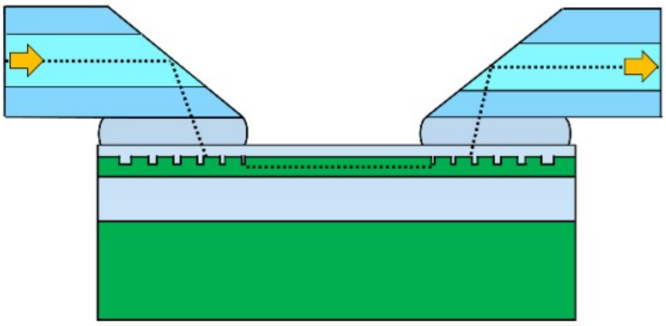


Figure 2. Light coupling geometry for a horizontal light grating coupler available as an open access building block that can be fabricated by CORNERESTONE SOI platform [2]

2.4 GlobalFoundries

45SPCLO is a 45 nm generation, SOI, CMOS technology that supports (ASIC) designs and custom logic designs. It offers power, area, and performance advantages and efficiency providing more data per watt per fibre per Laser. Monolithic integration of RF, digital and Si-Photonic circuits with higher energy efficiency and higher modulation speed. Ideal for applications like Automotive Lidar, IoT, Cloud, Frictionless Networking, Virtualization and Hierarchical AI [4].

2.5 ihp

ihp use monolithic photonic-electronic process, where the process uses the same Silicon wafer with localized SOI areas for photonics, bulk-like areas BiCMOS, and make use of common back end of line as modular process flows. Typical applications are datacenter interconnects 100-400G. ihp's monolithic electronic-photonic integration platform integrates the basic components of electro-optic transceiver, such as, modulators, drivers, and photodetectors on a single chip. This platform has SiGe Hetero-Junction Bipolar Transistors and full photonic device set for C/O-band . The ihp recipe is based on 200mm wafers with SOI areas for photonics and common Back End Of Line modular process flow. The platform has a range of flavors with a popular high performance SG25H5_EPIC that has BiCMOS technology with integrated Silicon Photonic devices. It combines SG25H5 BiCMOS process with RF performance (f_T/f_{max}= 220 GHz/290 GHz) and photonic devices [5].

2.6 Imec

Imec is an R&D hub for nano- and digital technologies, which offers photonics platforms based on silicon as well as silicon nitride. Imec's silicon photonics platform, iSiPP50G, is based on 130nm CMOS node process technology and co-integrates a wide variety of passive and active components to support a wide range of optical transceiver architectures at a data rate of 50Gb/s. The platform is based on SOI wafers with 220nm thick crystalline silicon waveguiding layer with options for three etch depths of 70nm, 160nm and 220nm. Additionally, the platform offers 160nm deposited poly-silicon layer for advanced grating couplers and waveguides. There are eight options for ion implants, four each for n-type and p-type, to enable phase shifters and high-speed silicon electro-optic modulators. Built-in germanium layers enable the fabrication of high-speed photodetectors and SiGe electro-absorption modulators (see Figure 3a). Thermal tunning can be achieved using metal heaters. Electrical access is established through standard CMOS interconnect scheme which includes tungsten contact plugs, two levels of metal interconnect based on copper and aluminum passivation finish. Fiber-to-chip light coupling is achieved either via grating couplers patterned on silicon or poly-silicon layers, or via broadband edge couplers which are combined with a deep etched trench at the edge of the chip to provide the optical access. The subset of iSiPP50G technology, called Passives+, consists of passive technology components, heater, two levels of metal interconnect and deep etched trench for edge-couplers. The platform also offers a vast validated component library and process design kits for leading photonics design software [6].

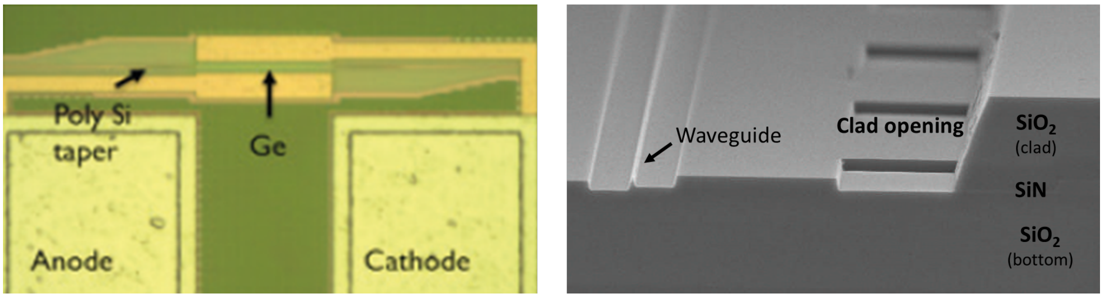


Figure 3. a) Microscopic top-down image of high-speed SiGe electro-absorption modulator of iSiPP50G. b) SEM cross-section image of clad silicon dioxide opening in BioPIX.

Imec's silicon nitride platform, BioPIX, is based on 180nm CMOS node process technology and it mainly targets applications in visible and near IR spectrum such as bio-photonics, LIDAR, quantum computing etc. The platform is based on PECVD silicon nitride, available in the thicknesses of 300nm and 150nm, which can further be partially etched to 150nm and 90nm respectively. Titanium nitride layer is used for heaters and aluminium layer is used for metal interconnect. The platform allows selective removal of clad silicon dioxide from top of the waveguides for sensing applications (see Figure 3b). Deep etched trench is also offered for edge couplers. The platform was validated through limited access MPW runs during EU project PIX4life, and it is offered as an open-access MPW services through EUROPRACTICE since 2020 [7].

2.7 LioniX International

LioniX International use their TriPleX Si_3N_4 waveguide platform that is based on alternating stacks of Si_3N_4 and SiO_2. This allows for several geometries to be processed, which in turn opens up more application specific optimum properties, this includes; Box Shell, which consists of a SiO2 box-shaped core surrounded by a Si_3N_4 shell. The Box Shell allows for two sub-variants, low index contrast and high index contrast, the former is typically used for low index coupling from glass fiber, while the latter used for telecoms applications [8]. Another type is Single-Stripe, this ultra-low propagation loss recipe shows propagation losses of 0.03 dB/cm at 1.55µm with a bend radius of 2mm. Other types include Symmetric Double-Stripe and Asymmetrical Double Stripe. The former is based on two stipes of Si_3N_4 with the same thickness separated by a layer of SiO_2 that allows for a propagation loss of 0.1dB/cm at 1.55µm with a bend radius of 100µm. The latter has a similar geometry, however the two Si_3N_4 thicknesses are different, where the upper stripe is thicker than the lower stripe, here the lower layer is optimized to couple to low index contrast such as glass fiber, while the upper stripe is optimized to allow for the tight radius bends with propagation losses comparable to the symmetric process [8]. Figure 4 shows an example layout of a ring resonator high order filter created by LioniX using their TriPleX Silicon Nitride waveguide platform.

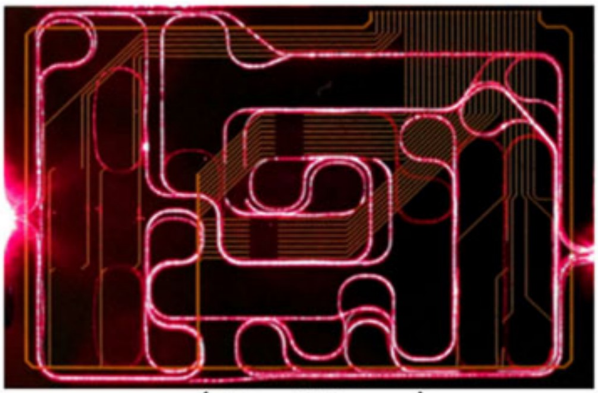


Figure 4. Picture of high order Silicon Nitride ring resonator filter by LioniX International [8]

3. OPEN ACCESS THROUGH EUROPRACTICE

In 1979 the IC community realized the need for open access to foundry services for electronic devices, and the Multi-Project Wafer (MPW) services was established through CMP in France and MOSIS in North America both launched in 1981 [9, 10]. Shortly after, in 1985, EURORPACTICE IC was established in broader Europe providing access to MPW services to the IC community, and later included Silicon Photonics for the PIC community [1]. The technologies mentioned in Section 2, and access to these foundries is possible through EUROPRACTICE, and in some cases the user may also access a foundry directly. Open access technologies allows for innovative research and development to occur without the need for each researcher or start-up to have their own fabrication facility, as they can operate as fabless enterprises and access industry grade tools and processes at affordable prices, with route to volume and quick scale up [11]. EUROPRACTICE helps innovators with their designs, adds design value to them, then takes the multi-user designs and works closely with the foundry as a single customer with many designs. Open access makes technology platforms accessible at affordable prices with minimal restrictions to the innovators, and lowers the barrier, enabling developments that would otherwise have been stifled. In fact, some foundries, such as CORNERSTONE who offer open source, license free Process Design Kits (PDKs) [2]. The standardization of process steps, issuing PDKs for users to follow, and providing an eco-system where users, designers, software companies, foundry services, packaging houses, and system integration facilities are all able to provide their technology and services while benefiting and enabling each other in the eco-system. While EUROPRACTICE opens up access to the full range of Silicon Photonics flavors, some material types, such as Silicon Nitride, have taken special attention with the functionality in lower wavelength ranges, opening up applications in Agro-Tech and biomedical or bio-sensing fields. For this reason, a dedicated open-access pilot line, PIX4life, was established, focusing solely on open-access to Silicon Nitride in life science applications [12]. There are brokers outside Europe also enabling open access to foundry services for their domestic and global users include, PETRA in Japan, IMECAS in China, and CMC Microsystems in North America to name but a few.

4. EXAMPLES AND EMERGING APPLICATIONS

With Silicon Photonics taking a more prominent position in shaping the direction of industry and technology, it has found uses in many fields such as telecoms, Datacom and especially in emerging applications such as bio-sensing applications. Figure 5 shows an image of a focused ultrasound detector developed by Technion [13] for intravascular photoacoustic imaging. This was achieved by integrating a miniaturized acoustic lens, made out of glass, with a silicon-photonics-based detector. A detection bandwidth of up to 80 MHz and lateral resolution beyond 50 µm was demonstrated with a lens diameter of 0.8 mm [13]. The device is transparent in the near-infrared window, simplifying its integration in a miniaturized probes. In this work, open access platform was leveraged to achieve the work, as the optical micro-resonators were fabricated in Silicon-on-Insulator technology at imec, scaling down to a few tens of microns with broad-bandwidth over 100MHz. In post-processing, polymer over-coating increases the sensitivity to few tens of Pascals, achieving sensitivity that enables bio-medical imaging. Finally, the Silicon resonators were fiber-coupled at Tyndall National Institute to allow interrogation and readout [1], all technologies; design software, foundry and packaging services were made accessible through EUROPRACTICE.

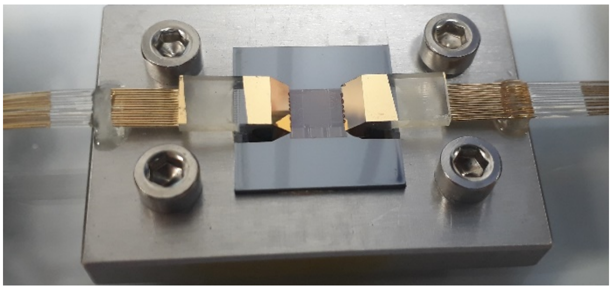
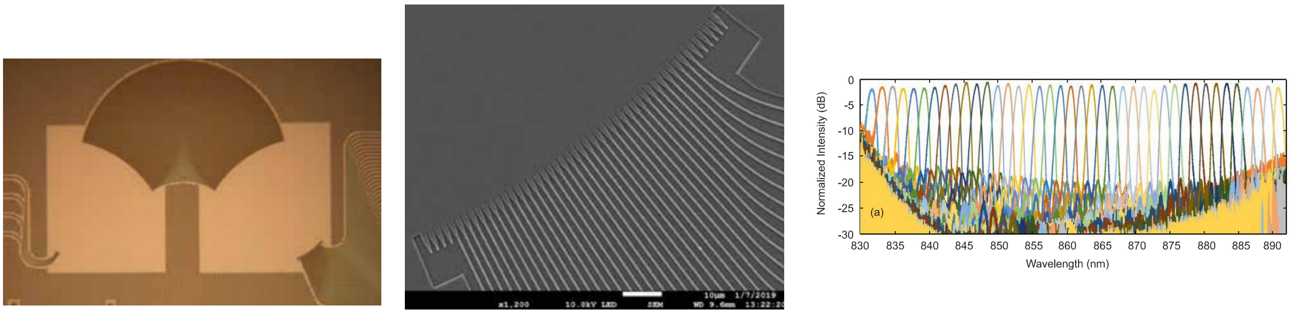


Figure 5. Silicon Photonic Array for Ultrasound Detection. A Silicon-photonics chip fabricated at Imec with specialized assembly at Tyndall of two fiber array attaches with gold coating [1]

Figure 6 shows images of a biomedical silicon photonic die with a compact arrayed waveguide grating spectrometer along with sample transmission data. In this work, a highly compact 40-channel Arrayed Waveguide Grating (AWG) fabricated on the silicon nitride platform for operation with a center wavelength near 860 nm for use in spectral domain optical coherence tomography. The total footprint of the AWG is 910µm × 680µm. The transmission spectrum of the fabricated device was measured. The AWG had a channel spacing of 1.5 nm and optical spectral range of 60 nm, in accord with the design. The measured insertion loss was 1.3 dB for the central channels and 1.8 dB for the outmost channels. The inter-channel crosstalk varied from 17.2 dB to 19.7 dB for the central 20 channels [14]. This was enabled by the MPW service from imec under the PIX4life and EUROPRACTICE silicon nitride MPW.



a) 40-channel AWG spectrometer

b) SEM image of parabolic tapers in the AWG spectrometer

c) Experimental transmission of the AWG spectrometer

Figure 6. Compact arrayed waveguide grating spectrometer for spectral-domain optical coherence tomography at 860 nm center wavelength on silicon nitride platform [1]

5. SUMMARY

Silicon Photonics technologies made available through open-access platforms like EURORPACTICE continue to play an essential role in bolstering the European position in photonic integrated circuit leadership. Silicon Photonics is an essential component for the progress of technology in a wide range of fields from telecoms, Datacom, and 5G to bio-sensing, life sciences, Agro-Tech, security and much more. This paper presented a summary review of some of the foundry services offering Silicon Photonics, comparing the key technologies available to European innovators. Table 1 acts as a quick look up guide for users looking to make use of Europe's Open Access Silicon Photonic Platform through EUROPRACTICE.

Table.1 Look up table for the key Silicon Photonic foundries with Open-Access via EUROPRACTICE, comparing their primary Silicon platform, wavelength of operation, and their typical fields of application

Foundry	Si-Platform	Wavelength of Operation	Typical Applications
AMF	SOI 220nm	Mid Near IR to mid Mid IR	Datacom, Telecoms, Sensing
CEA Leti	SOI 220nm, SOI 310nm , Si3N4, Si-Si3N4	Mid Near IR to mid Mid IR Visible, Near IR, mid Mid IR	Datacom, Telecoms, Sensing imaging, bio-life-sciences, Agro-Tech, Datacom, Telecoms,

			Sensing
CORNERSTONE	SOI 220nm, SOI 340nm, SOI 500nm, Si3N4	Mid Near IR to mid Mid IR Visible, Near IR, mid Mid IR	Datacom, Telecoms, Sensing imaging, bio-life-sciences, Agro-Tech, Datacom, Telecoms, Sensing
GlobalFoundries	45 nm generation, SOI, CMOS	C-band (1550 nm) coherent transceivers modules, O-band (1310 nm) direct detect transceivers	Automotive Lidar, IoT, Cloud, Frictionless Networking, Virtualization and Hierarchical AI
ihp	BiCMOS, SiG	Mid Near IR to mid Mid IR Visible, Near IR, mid Mid IR	Datacom, Telecoms, Sensing, bio-life-sciences, Agro-Tech, Datacom, Telecoms, Sensing
imec	SOI 220nm, SiN 150nm, SiN 300nm	Mid Near IR to mid Mid IR Visible, Near IR, mid Near IR	Datacom, Telecoms, Sensing Imaging, bio-life-sciences, Agro-Tech, Datacom, Telecoms, Sensing
LioniX International	Si3N4 (defined by wavelength of operation: Visible, 850nm, 1550nm)	Visible, Near IR, mid Mid IR	Imaging, bio-life-sciences, Agro-Tech, Datacom, Telecoms, Sensing

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