Programmable Photolithographic Masks for Novel Trust and Assurance Approaches

Ezra Hall, Jed Rankin
GLOBALFOUNDRIES
Essex Junction, Vermont, 05452

Alok Vaid
GLOBALFOUNDRIES
Malta, New York, 12020

Abstract-As economic and technical motivations drive advanced node integrated circuit (IC) complexity to 100's of millions to billions of transistors per IC, the ability to tailor or modify an IC post design and fabrication becomes increasingly important. At the same time, adversaries are becoming increasingly skilled at compromising ICs, driving the need for mitigations such as obfuscation and individual IC authentication and authorization. Existing approaches can utilize volatile and/or nonvolatile memory, combined with embedded logic, but such approaches have limitations. In this paper a novel "on the fly" programmable photolithographic mask structure and associated manufacturing method is described to implement an approach suitable for non-disruptive integration into high volume manufacturing environments. With this new ability to tailor each individual IC during semiconductor manufacturing, an entire new class of IC designs is possible through customization of millions of dense embedded hidden non-differentiated on chip structures, on an individual IC basis. Novel trust and assurance approaches, to combat counterfeiting and to thwart nation state adversaries, through the implementation of new obfuscation, authentication keying, feature tailoring, functionality modification, and proof of provenance, are possible with this new technology.

Keywords: Programmable; Mask; IC; Obfuscation; Secure;

I. Background

Existing high volume manufacturing technology results in a permanent fixed chrome on glass photolithographic mask set for each design. Depending upon the technology and design complexity, generally between 20 and 80 mask levels are required per design. The existing mask structure is depicted in Figure 1, below.

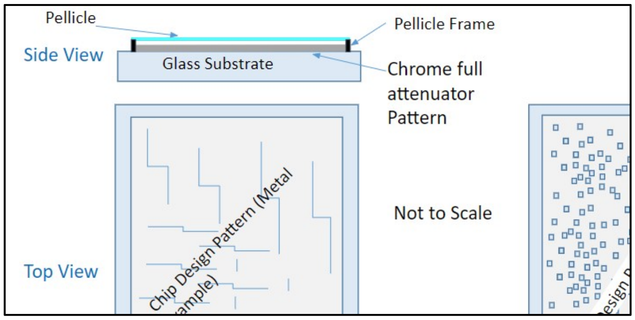

Figure 1: Existing mask Structure

To fabricate such a mask, one starts with a substrate of blank chrome, or other partial or full attenuators, on glass. Photolithographic techniques are then utilized to pattern and etch the chrome or other attenuators, defining the fixed design structures for that mask level. A frame and pellicle is then placed above the pattern to prevent dust or other contaminants from being within the focal plane of the chrome pattern during lithographic exposure during the manufacturing process.

During fabrication, masks are utilized in the semiconductor fab, at each of the corresponding hundreds of process steps, to expose each die site on the wafer to each mask level from a given mask set. This sequence is repeated many times during manufacturing for each mask level in the mask set, the corresponding steps for each such sequence are outlined in Figure 2, below.

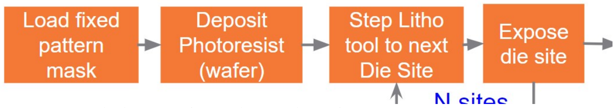

Figure 2: Existing mask use in semiconductor manufacturing

Such existing fixed pattern chrome on glass masks are suitable for high volume manufacturing of permanent unchanging designs. Such masks are robust and fab equipment is optimized to produce high volumes of parts utilizing these masks.

II. Novel "on the fly"

The novel structure creates new programmable masks that fits within existing fab process equipment while allowing programmability on a per die basis. The programmable structure utilizes existing chrome on glass technology to define spatial frequency of all programmable structures, which are made programmable with the integration of a spatial light modulator over said structures. Such integration imparts the ability to expose (or not expose) each structure, see Figure 3, below, for a pictorial of this new structure.

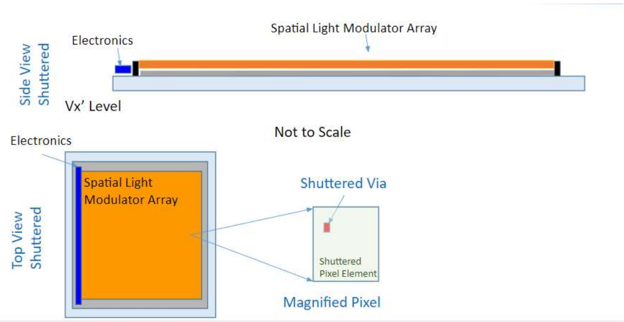

Figure 3: Pictorial of novel mask structure

This mask technology enables the definition of structures that can be programmed, such as a subset of vias between metal levels. The base mask for a given via level would define all permanent vias (millions to billions), whereas a second mask for that via level integrates the spatial light modulator to enable programmability of a subset of the via level (thousands to millions) each to be individually and programmatically included or excluded from exposure via programmability. This example is depicted in Figure 4, below.

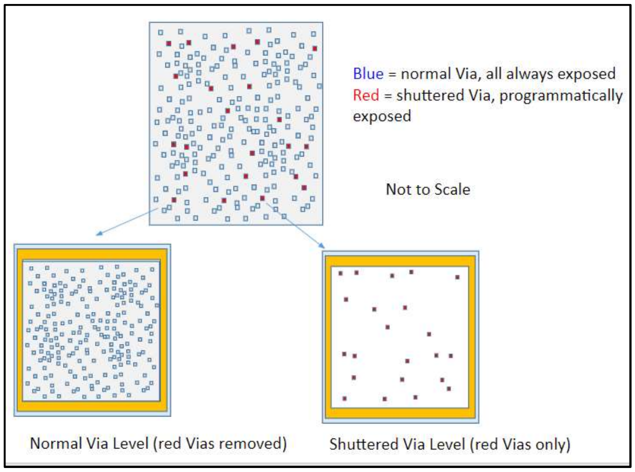

Figure 4: Programmable via level example

III. Methodology for use in high volume manufacturing

During manufacturing, at least one level (via level in this example) includes a secondary mask to define programmable structures. The corresponding manufacturing sequence is as shown in Figure 5, below:

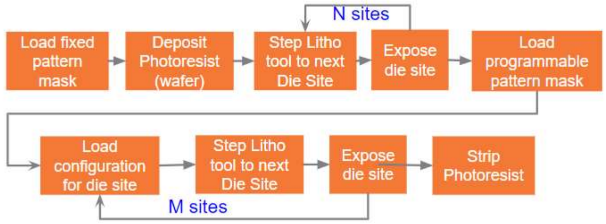

Figure 5: Manufacturing flow utilizing novel mask structure

Such a technique could be utilized for more than one via level for example, enabling a complex level of individual IC programmability.

III. Operability

To create high performance ICs, semiconductor manufacturing requires control of processes within extremely tight process windows, and operating in relatively harsh environments. Creation and operation of a dynamically configurable mask, such as the shuttered via mask shown above is both achievable within the environmental concerns, and is actually based upon leveraging the process window challenges.

In most lithographic processes using chemically amplified resists, a critical radiation dose must be delivered to create sufficient polymeric de-protection to allow for dissolution during subsequent develop steps(Ito, 1999). Manufacturing processes are optimized to ensure sufficient dose control and resist sensitivity controls to ensure this threshold is not encountered during normal manufacturing variations. Figure 6, below, shows the relationship between printed contact dimension (y-axis) and dose (x-axis); identified zone 3 exemplifies dose regions where insufficient optical radiation is delivered and therefore the patterns fail to resolve.

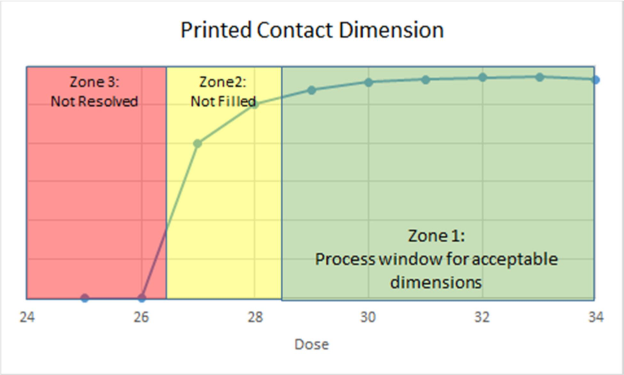

Figure 6: Contact dimension vs. dose

In addition to lithographic resolution limits shown above, there are also process related limits to the acceptable feature dimensions. Zone 2 depicted in Figure 6, above, identifies the dimensional regime where the via can resolve lithographically, but the fill process fails reliability requirements.

In the case of the dynamically configurable mask, we leverage this relationship to modulate the local dose delivered through portions of the mask to change from a regime centered in the printable region to locally printing contacts in the non-resolved regime. As shown above, in many cases, less than 10% reduction in dose can result in catastrophic failure.

One of the key principles of the dynamically configurable mask is the use of an integrated spatial light modulator for reducing the local radiation dose transmitted through the mask features. While other spatial light modulators can be used, the most implementable is a Liquid-Crystal-Display (LCD). Although LCDs are traditionally designed for use with optical light, the properties of the reconfigurable nematic crystals are also adept at modulating light transmission in the ultraviolet and deep ultraviolet regions used by most lithographic scanners. Figure 7, below, shows the viable functioning of a nematic liquid crystal display at a number of wavelengths. Although there is less attenuation (darkening) for the ultraviolet 365nm light than the optical light, there are still 10 orders of magnitude difference in optical flux (I) between a positive and negative 10v bias. Additionally, the difference between 0V and 10V is still greater than the 10% attenuation required to modulate the printability shown above.

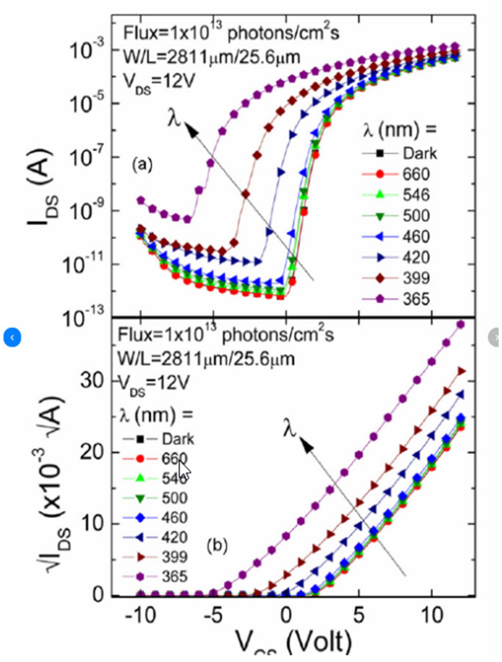

Figure 7: Nematic LCD performance vs. voltage (Chuang et al, 2008)

Figure 3, above, also shows the electronic control module sitting adjacent to the SLM/pellicle, but on the glass surface. As long as the total vertical height is restricted below the top surface of the pellicle, compatibility with the scanner can be maintained. The interface to the electronic control module can be done in four ways

- Direct electrical connection (to the SLM)
- Indirect electrical connection (to the surface of the mask, which is in kind connected to the SLM
- Remote communication (RF), and/or power (induction)
- Pre-programming based on time and/or mask movement (relying on accelerometers within the electronic control module)

As shown above, an LCD is capable of attenuating light sufficient for modulating printability. Figure 3, above, shows that in the primary embodiment for creating a dynamically programmable mask, the pellicle, which is used to protect against contaminates, is replaced in concept with the LCD programmable spatial light modulator. Given the design of the reticle handlers, and optical systems within the scanners, there is limited ability to extend the overall height of the mask when replacing the pellicle with a SLM, so the SLM elements will actually be closer to the imaging surface of the reticle. This is beneficial since it will be closer to the focal plane, therefore modulations will have more direct impact on the light. Yan et all have presented how particles greater than 175 um on pellicles 5mm above the imaging surface can cause 10% local dose deviations with 365nm light with a partial coherence of 50 %. This result is shown in Figure 8, below.

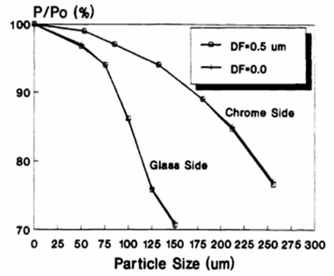

Fig. 7 P/P_0 as a function of pellicle defect size with and without the presence of 0.5 μm defocus.

Figure 8: Light transmission intensity versus particle size on pellicle and glass side

Given the construct of the spatial light modulator being effectively below the top surface of the pellicle and the ability to modulate the exposure conditions (sigma and NA) to maximize dynamicity, this defines a lower limit of ~200nm grid for the SLM addressability. In reality, much larger addressable units (<10um) would be used to ensure alignment to the contact holes defined in the quartz. In addition, the penumbra of attenuation extends laterally as well, requiring a similar “dead zone” of design space which must be restricted for patterning.

Dynamically programmable photomasks can be made using largely existing technology. While the performance of the mask will be degraded by the addition of a spatial light modulator to the optical path, the degradation can be accounted for in mask and process design. Creation, attachment, and operation of the electronic control module does require some invention, however we are confident it can be done within the existing design constraints of existing manufacturing systems, with minor modifications.

IV. Example use cases

Novel IC design implementations are possible utilizing this technology, through inclusion of new features which can be both varied and hidden on a per die basis via use of programmable masks. The following simplified examples begin to outline this new trade space.

Obfuscation can be complicated through the introduction of programmable features, confounding reverse engineering attempts. Design structures for sensitive data elements could be connected in varied fashion, modified on a per die basis. In this manner, if an adversary delayered and reverse engineered a single die, such results would not map to other die as each die implements varied structures. Die to die correlation attempts would be thwarted, and reverse engineering efficacy would be reduced or nearly eliminated.

Through the use of distributed and embedded programmable structures, structures effectively hidden from adversarial discovery, hidden per die signatures could recorded at the time of manufacture. Thousands of programmable vias, to be used for the purpose of recording unique signatures on a per die basis, could be distributed on a single level, or across multiple levels, amongst the billions of vias normally present. Unlike a physically uncloneable function, or an embedded non-volatile memory array, discovering such distributed programmable elements would be akin to searching for a needle in a haystack.

Through inclusion of spare circuitry, bug fixes could be implemented through the simple act of reconfiguring logic through programmable vias defined on the fly. This capability would avoid lengthy delays and costs associated with fabricating new mask sets for each design EC, and could even enable multiple versions of a single design to be expressed in a manner of seconds across each die on a single wafer. Wafers could be staged within the fab, with the majority of process steps completed, and final design tailoring could be completed before the wafers exit the fab.

While many use cases predominately hold value for government applications, the ability to modify ICs could hold value to commercial applications as well.

V. Summary and next steps

As described above, creation of a dynamically programmable photomask is feasible, which can be used in conjunction with traditional mask and wafer manufacturing to create individually customized ICs for a number of use cases. While there are several other challenges, such as modification of the design and tap-eout to allow for the primary patterning of the “programmable photomask”, the primary challenge relates to integration of the spatial light modulator onto a photomask and exposure system. Although the feasibility of the components (design, SLM, active programming exposure, and subsequent wafer processing) can be demonstrated, additional work is required to reduce these processes to support “high volume manufacturability”.

The first task to undertake will be the integration of a spatial light modulator first onto a traditionally patterned photomask, in such a manner that it will have minimal degradation to the lithographic function of the photomask features, yet while providing enough modulation to “turn off” the transmission from specific mask features, provide a means for active programming inside the lithographic scanner, and to achieve sufficient durability to the radiation and environment experienced in the scanner. Key items for consideration include:

- Determining SLM location (in place of pellicle or on back of mask) based on optical path, required addressability frequency, and reticle chuck-compatibility.
- Modeling radiation attenuation capability of SLM given SLM technology, placement in focal path and specific exposure wavelength
- Development of solution for attaching SLM and additional components (power, connectivity) to photomask -- likely leveraging existing pellicle technology.
- Optimizing mask design and exposure conditions to leverage radiation attenuation differences
- Designing and creating SLM compatible with exposure system
- Fabricating test masks complete with SLM
- Demonstration of lithographic programmability on single exposure
- Integration of programmable via layer with traditional “parent” via layer
- Demonstration of programmability on integrated IC

In addition, the durability and reliability of the solution will need to be tested. This will require extended exposure of the SLM to the exposure environment, including radiation, the pattern placement accuracy of a dual patterning system, and the reliability of the process for differentiating between attenuated and non-attenuated exposure regions.

Other key challenges will be in integration of the dynamic programming with the exposure system, including definition of protocol (RF vs. direct connection), powering (battery vs. external vs. induction), software integration (exposure system and mask dynamic programming). This will likely require co-development of a solution with the original photolithographic tool manufacturer, which will be complicated by any necessary security concerns.

In summary, we believe there is sufficient demonstration of the feasibility of the operational components required to produce, and use a programmable photomask.

Additional design optimization is needed to ensure compatibility with specific implementation constraints, but there are no fundamental limitations precluding implementation. Collaboration will be required with existing industry supporters, such as lithography exposure tool suppliers to create a robust, manufacturable solution, but there are no obvious technical limitations to a successful implementation.

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