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Modeling and Characterization of Optical TSVs

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ABSTRACT

In future, computing platforms will invoke massive parallelism by using a huge number of processing elements. These elements need broadband interconnects to communicate with each other. Following More-than-Moore concepts, soon large numbers of processors will be arranged in 3D chip-stacks. This trend to stack multiple dies produces a demand for high-speed intraconnects (within the 3D stack) which enable an efficient operation. Besides wireless electronic solutions (inductive or capacitive as well as using antennas), optical connectivity is an option for bit rates up to the Tbit/s range, too. We investigated different candidates for optical TSVs. For optical transmission via optical Through-Silicon-Vias, we were able to demonstrate negligible losses and dispersion.

Keywords: integrated optoelectronics, multichip modules, through-silicon vias

1. INTRODUCTION

The continuous advances in microelectronics enable the ongoing progress and the creation of new applications in computing, sensing and communications. The driver for the unbroken success of this key technology is the reduction of feature sizes resulting in an exponentially growing number of electronic components that can be integrated on a single chip of the same size, well-known as Moore's law. Reaching physical boundaries, the further reduction of the feature size itself is limited. As a consequence, new approaches have to be found to maintain this exponential growth. Stacking of multiple chips is a promising approach to enhance the functionality of semiconductor devices while still lowering the footprint. This comes along with innovative packaging solutions.

Besides thermal management, connectivity is another crucial point when 3D chip structures come into play. Through-silicon vias¹ (TSVs) are the key technology for chip-stack intraconnects. Copper-based solutions² for electrical connections are the traditional approach. Ultra-thin TSVs³ have been presented. Also, reliability is an important point⁴ for microelectronics. A high bandwidth is the major performance indicator for TSVs, so one of the applications⁵ is to address bandwidth bottlenecks between an ASIC and its external memory.

However, optical lines have the potential to outperform copper-based connections in terms of bandwidth at the cost of more complexity due to electro-optical and opto-electrical conversion. Once converted, though, transmission distances are far less critical than in case of electrical interconnects. Hence, first optical systems⁶ for chip-to-chip and chip-stack-to-chip-stack communication have been proposed. Multi-processor configurations are the driver for optical networks⁷⁻⁹ that connect chips. Optical TSVs are needed^{10,11} for these optical networks. Even WDM concepts¹² are discussed.

This paper is structured as follows: First, the modeling of optical TSVs is introduced. Then, the experimental results from the TSV characterization follow and will be discussed and summarized.

2. OPTICAL TSV MODEL

The wavelength of the source and the corresponding waveguide material are chosen first when designing optical transmission systems. The intended scenario within the scope of 3D chip integration (see Figure 1) takes into account VCSELs and photodiodes,¹³ i.e. a 850 nm laser source with 20 GHz RF bandwidth, a rise time of 10 ps

Figure 1. 3D chip integration scenario with TSVs

and a beam angle $\Phi_0 = 12^\circ$. The photodiode has an RF bandwidth of 30 GHz, a rise time of 9 ps and an active region diameter of $d_{PD} = 15 - 45 \mu\text{m}$.

To simplify the measurements, a 50/125 μm multi-mode fiber (MMF) is butt coupled to the TSV from both sides (see Figure 2). The fibers are connected to pigtailed VCSEL and photodiode modules with the characteristics mentioned above. The standard MMF has a numerical aperture of $A_N = 0.2$. This corresponds to an angle $\Phi_0 = 11.5^\circ$ which is in the range of the VCSEL beam divergence. Hence, realistic values for loss and transmission can be obtained.

Figure 2. Measurement setup with MMF attached to TSV: principle (left) and lab setup (right)

2.1 Air-filled TSV

The first candidate for optical transmission is an air-filled TSV, i.e. free space transmission. This kind of TSV can be manufactured¹⁴ most easily. Approximating the propagation of the optical field emitted by the laser as Gaussian beam, the beam width w can be written as function of the distance to the emitter

$$w(z) = w_0 \sqrt{1 + \left(\frac{\lambda_0 z}{n\pi w_0^2} \right)^2} \quad (1)$$

with the initial beam width w_0 at the distance $z = 0$, the wavelength $\lambda_0 = 850 \text{ nm}$ and the refractive index $n = 1$ for air. For distances $z > 10\lambda_0$, the far field approximation

$$w(z) = \frac{\lambda_0 z}{n\pi w_0} = \Phi_0 z \quad (2)$$

with the beam angle Φ_0 can be applied. This is possible for all reasonable TSV geometries ($z > 8.5 \mu\text{m}$). However, not all of the divergent beam is lost in the silicon wafer. Although there is no waveguiding, those parts of the beam which are widened more than the TSV diameter are reflected at the interface between silicon and air due to the huge index difference between the air and the surrounding medium ($n_{\text{sur}} = 3.66$ for silicon

Figure 3. Propagation model for air-filled TSV

at 850 nm). With short distances in the range of hundreds of micrometers, just a few reflections can occur as depicted in Figure 3.

The above mentioned number of reflections depends on the diameter of the TSV d_{TSV} , its length l_{TSV} and the incident beam angle Φ_0 . Reflections occur starting from the angle

$$\varphi_{min} = \arctan \left(\frac{\frac{d_{TSV}}{2}}{l_{TSV}} \right). \quad (3)$$

The maximum angle for one reflection φ_{1R} , two reflections φ_{2R} , and generalized k reflections φ_{kR} inside the TSV can be computed by

$$\varphi_{kR} = \arctan \left(\frac{\frac{d_{TSV}}{2}}{\frac{l_{TSV}}{2k+1}} \right) \quad (4)$$

with $k \in \mathbb{N}$. The number of reflections k is determined by requiring $\varphi_{kR} \leq \Phi_0$. The angle of transmission into the substrate φ_2 can be calculated by Snellius' Law at the interface between air (n_{air}) and surrounding medium (n_{sur})

$$\varphi_2 = \arccos \left(\frac{n_{air}}{n_{sur}} \cos \varphi_1 \right). \quad (5)$$

Since the physical principle is not total internal reflection, different reflection factors (r_{TE} , r_{TM}) for TE and TM have to be considered

$$r_{TE} = \frac{n_{air} \sin \varphi_1 - n_{sur} \sin \varphi_2}{n_{air} \sin \varphi_1 + n_{sur} \sin \varphi_2} \quad (6)$$

$$r_{TM} = \frac{n_{air} \sin \varphi_2 - n_{sur} \sin \varphi_1}{n_{air} \sin \varphi_2 + n_{sur} \sin \varphi_1}. \quad (7)$$

Smaller angles cause higher reflection factors. The loss due to the transmission into silicon can be calculated by summing up the integral over the angular spectrum (assuming a homogeneous power distribution) for the number of reflections k . Given the relatively short distances of TSVs, only a few reflections have to be taken into account, so that for the sake of simplicity the result is given here for two reflections

$$P_{loss,TE|TM} = \int_{\varphi_{min}}^{\varphi_{1R}} (1 - |r_{TE|TM}|^2) d\varphi + \int_{\varphi_{1R}}^{\Phi_0} |r_{TE|TM}|^2 (1 - |r_{TE|TM}|^2) d\varphi \quad (8)$$

Due to the cylindrical symmetry of the TSV, the total loss shows equal contribution from TE and TM

$$P_{loss} = \frac{P_{loss,TE} + P_{loss,TM}}{2}. \quad (9)$$

For a typical TSV length of $l_{TSV} = 370 \mu\text{m}$ and a diameter $d_{TSV} = 48 \mu\text{m}$, this model yields a loss $P_{loss} = 2.3 \text{ dB}$ due to the transmission into the silicon.

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2.2 Waveguide TSV

To guide the optical field inside a TSV, its filling needs a higher refractive index than the surrounding. Having a comparably high refractive index, silicon has to be shielded from the TSV filling using a lower refractive index material. From a technological point of view¹⁴ SU-8¹⁵ is a promising material. To accomodate the beam divergence ($\Phi_0 = 12^\circ$ for VCSEL) and taking into account the refractive index of the core material SU-8 ($n_c = 1.56$), the numerical aperture

$$A_N \geq \sin \Phi_0 = 0.21 \quad (10)$$

the maximum refractive index of the shielding material acting as cladding can be calculated

$$n_{cl} \leq \sqrt{n_c^2 - A_N^2} = 1.546. \quad (11)$$

Silicon dioxide ($n_{\text{SiO}_2} \approx 1.47$) is a good candidate for shielding and can be easily manufactured. Figure 4 shows the principle structure of the waveguide TSV. Because the deposition of the silicon dioxide layer is a time consuming process, it should be just as thin as necessary. However, being too thin, the field may interact with the silicon bulk material causing high losses. Using numerical field simulations, the minimum thickness for the silicon was estimated. As a rule of thumb, the thickness should exceed half of the wavelength (i.e. 425 nm for the VCSELs at $\lambda = 850$ nm used).

Figure 4. Waveguide TSV

2.3 Performance estimation

For a multi-mode waveguide, mode dispersion is one of the major impairments that limits the transmission bandwidth. The available bandwidth can be calculated from the difference between the propagation time of the fastest ($t_{g,\min}$) and the slowest ($t_{g,\max}$) mode

$$\Delta t_g = t_{g,\max} - t_{g,\min} = t_{g,\min} \left(\frac{n_c}{n_{cl}} - 1 \right) \quad (12)$$

with the refractive index of the filling of the TSV n_c , its shielding n_{cl} and the propagation time of the fastest mode (axial mode)

$$t_{g,\min} \approx \frac{L}{c_0} n_c \quad (13)$$

taking into account the length of the TSV L and the speed of light in vacuum c_0 . For rectangular pulses, the pulse broadening

$$\sigma = \frac{\Delta t_g}{\sqrt{12}} \quad (14)$$

leads to a baseband bandwidth of

$$f_B = \frac{0.2}{\sigma}. \quad (15)$$

Figure 5. Eye diagrams: back-to-back (reference, upper), air-filled TSV (middle) and waveguide TSV (lower), 10^{-6} BER

For the given values, this computes (see equations (14) and (15)) to a broadening per unit length of 8.84 ps/m which corresponds to a bandwidth per unit length of 22.6 GHz/m. Even for connections in the cm range, this means THz bandwidths. Anyway, the tendency is to use even thinner interposers (e.g. 200 μm thickness) which means shorter TSVs with even more bandwidth. Hence, mode dispersion is not an issue for chip-to-chip connections. The material dispersion

$$D_M = -\frac{\lambda}{c_0} \frac{d^2 n_c(\lambda)}{d\lambda^2} \quad (16)$$

depends on the wavelength-dependent refractive index of the material. It is much smaller than the mode dispersion. With a very high normalized frequency

$$V = \frac{\pi d_{\text{TSV}}}{\lambda} \sqrt{n_c^2 - n_{cl}^2}, \quad (17)$$

the waveguide dispersion is also very low. For SU-8, a chromatic dispersion (consisting of material and waveguide dispersion) of about 0.03 ps/nm is accumulated over 1 cm transmission distance which enables THz bandwidth and therefore may be ignored.

Loss can be caused by the material itself or by the geometry of the waveguide. Especially surface roughness and other inhomogeneities¹⁶ have significant influence. For SU-8 based multimode waveguides comparable to the optical TSVs attenuations as low as 0.36 dB/cm¹⁷ could be reached. Since our technology provides very low surface roughness (below 20 nm), and TSV distances do not exceed centimeters, the attenuation is not critical. Additional loss is caused by the coupling of the emitter and receiver to the TSV, especially when the TSV is smaller than the active areas of laser or photodiode.

3. MEASUREMENTS

Both types of TSVs, air-filled and polymer-filled TSVs (waveguide TSVs) have been characterized in terms of transmission performance. Using MMF-coupled VCSELs and photodiodes, data rates of up to 26 Gbit/s could be achieved. The eye diagrams in Figure 5 show that the transmission data rate was limited by the transmitter and receiver - the TSVs do not change the eye characteristic (besides loss). It is worth mentioning that the Q factor of all eye diagrams is similar resulting in a BER of approximately 10^{-6} .

Plotting the bit error rate measured with a SHF BER measurement system against the received optical power underlines the superior transmission properties of the optical TSVs. To be able to measure low BERs, the bit rate had to be reduced to 18 Gbit/s. As expected, the BER vs. received optical power curves (Figure 6) do not show any penalty due to the TSV realization. Moreover, different realizations of the same type of TSV have similar behavior. Therefore, it is expected that the optical TSVs have a bandwidth of up to THz. However, the lack of suitable transmitters and receivers makes it difficult to measure with such high bandwidths.

4. CONCLUSION

Optical TSVs can be used to provide extremely high bandwidths and low loss for intra-chip and inter-chip connections. Two types of TSVs have been manufactured: Air-filled TSVs and polymer filled TSVs. The physical principle of both is completely different: The polymer filled TSV is an optical waveguide based on total internal reflection while the air-filled TSV acts as free-space transmission. Both have low losses and a high bandwidth of more than 20 GHz has been measured. The bandwidth is expected to be higher than several hundreds of GHz. However, the current bottleneck is the optical transmitter and receiver. Moreover, error-free data transmission has been demonstrated up to 26 Gbit/s.

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Figure 6. Bit error rate vs. received optical power for TSVs at 18 Gbit/s

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