Measurement and Analysis of Glass Interposer Power Distribution Network Resonance Effects on a High-Speed Through Glass Via Channel

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Abstract—In this paper, we measured and analyzed glass interposer power distribution network (PDN) resonance effects on a high-speed through glass via (TGV) channel for the first time. To verify the glass interposer PDN resonance effects on the TGV channel, glass interposer test vehicles were fabricated. With these test vehicles, glass interposer PDN impedance, channel loss, far-end crosstalk, and eye diagram were measured. Based on these measurements, glass interposer PDN resonance effects on the signal integrity of the high-speed TGV channel are analyzed. Due to low loss of the glass substrate, high PDN impedance peaks are generated at the resonance frequencies. High PDN impedance peaks at the PDN resonance frequencies, which affect return current of the TGV channel, increase channel loss, crosstalk, and PDN noise coupling in the frequency domain and degrade eye diagram in the time domain. To suppress these glass interposer PDN resonance effects, a ground shielded-TGV scheme is proposed. The proposed ground shielded-TGV scheme includes two ground TGVs 200 μm away from the signal TGV considering the design rules and includes package ground underneath the glass interposer. Effectiveness of the suggested grounding scheme on the resonance effects suppression is verified with three-dimensional electromagnetic simulation. The proposed shielded-TGV design successfully suppressed the glass interposer PDN resonance effects that results in the suppression of insertion loss, shielding of the crosstalk, and improvement of the eye diagram of the high-speed TGV channel.

Index Terms—Glass, high-speed channel, interposer, measurement, power distribution network (PDN), resonance, through glass via (TGV).

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I. INTRODUCTION

Recently, the realization of high-speed electrical systems with wider bandwidth, superior electrical performances, smaller dimensions, and lower manufacturing cost has been a continuous challenge. 2.5-Dimensional (2.5-D) integration based on through silicon via (TSV) and silicon interposers has attracted substantial attention as a promising solution toward current industrial challenges due to their improved electrical performances and compact design [1]–[4]. The TSV technology enables vertical interconnection between homogeneous or heterogeneous integrated circuits (ICs) that provide much shorter channel length compared to the conventional, lateral integration. The silicon interposer technology increases ICs’ integration density and the number of channels since it allows very fine pitch metallization [5]. Because of these merits, 2.5-D integration based on both TSV and silicon interposer technology enables the system to transmit a much larger amount of data simultaneously that can significantly increase the system bandwidth [6]. Even though the silicon interposer-based 2.5-D integration provides promising solutions to current industrial challenges, the manufacturing cost still remains high due to the following reasons: limited wafer size and additional fabrication steps required to isolate the conductors from the conductive silicon substrate. Furthermore, the conductivity of the silicon substrate can cause significant signal integrity (SI) issues [7].

In order to mitigate these problems, glass as an interposer substrate material is proposed. Glass interposers have several advantages namely: excellent dimensional stability, closely matched coefficient of thermal expansion (CTE) to silicon dies to be mounted, availability of glass substrates in large and thin panel sizes compared to that of silicon wafers, and lastly, excellent electrical resistivity of the glass substrate that contributes to low signal loss up to gigahertz range [8]. Therefore, 2.5-D integration based on the glass interposer is a potential means of achieving high-bandwidth and high-integration density electrical systems with reduced manufacturing cost.

The glass interposer consists of a low-loss glass substrate, polymers, through glass vias (TGVs), and fine-pitch metals for designing channels and power distribution networks (PDNs) on both sides of the thin glass substrate. The PDN of the glass interposer consists of power and ground planes for supplying a stable power to the assembled dies. Since the glass substrate has high-resistivity, low-loss channel characteristic is maintained up
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Fig. 1. (a) Low loss of the glass substrate generates high PDN impedance peaks at the resonance frequencies. These high impedance peaks cause signal and power integrity problems. (b) Transmitted signal through high-speed TGV channel is distorted by the glass interposer PDN resonance. Glass interposer PDN resonance generates high PDN impedance peaks which disconnect return current of the TGV channel. Therefore, channel loss and crosstalk increase. Received signal is deteriorated significantly due to the glass interposer PDN resonance associated with the low loss of the glass.

to high-frequency range that enables the high-speed signaling. However, this high-resistive, low-loss glass substrate generates high PDN impedance peaks at the PDN resonance frequencies shown in Fig. 1(a). These high PDN impedance peaks disconnect the return current of the TGV channel, increase insertion loss of the channel, and induce crosstalk problems. Fig. 1(b) describes the degradation of the received signal in the high-speed TGV channel due to the glass interposer PDN resonance. Furthermore, when the return current of the TGV channel is disconnected due to high PDN impedance at the resonance frequencies, the return current is loaded to the glass interposer PDN that propagates through the PDN and causes PDN to channel crosstalk problems. In organic packages and PCBs, previous studies report that at the PDN resonance frequencies, high PDN impedance peaks are generated that cause severe signal and power integrity problems [9]–[13]. Also signal and power integrity problems and their interactions are widely explored topics at the organic package and the PCB level [14], [15]. Since the resistivity of the glass substrate is higher than that of organic or silicon, sharper and higher PDN impedance peaks are generated at the PDN resonance frequencies in the glass interposer [16], [17]. Therefore, a study dealing with the signal/power integrity analysis of the glass interposer at the PDN resonance frequencies is necessary.

In this paper, we first measure and analyze the glass interposer PDN resonance effects on a high-speed TGV channel. Single-ended TGV channels and glass interposer PDN impedance are measured and analyzed in the frequency domain and the time domain. To experimentally verify the studies, glass interposer test vehicles, composed of a low-loss glass substrate, PDNs, and TGV channels are fabricated for measurement. With these test vehicles, glass interposer PDN impedances, channel losses, and crosstalks are measured in the frequency domain up to 20 GHz and eye diagrams are measured in the time domain with and without the input signal’s data rate corresponding to the PDN resonance frequencies. Based on these measurements, the glass interposer PDN resonance effects on the SI of the high-speed TGV channel are analyzed. High PDN impedance at the resonant frequencies causes return current discontinuity of the TGV channels, resulting in increased channel loss, PDN noise coupling, and crosstalk. Due to these problems, the received eye diagram of the TGV channel is degraded severely.

To suppress these glass interposer PDN resonance effects on the TGV channel, we propose the ground shielded-TGV scheme to provide a return current path that is less affected by the resonance and crosstalk effects. The proposed design includes two ground TGVs placed 200 μm away from the signal TGV considering the design rules and package ground underneath the glass interposer. We verified the effectiveness of the proposed grounding scheme for the glass interposer PDN resonance suppression in the simulation level. The proposed ground TGV design successfully suppressed the glass interposer PDN resonance effects by providing the return current path less affected by the PDN resonances. By adopting the proposed ground TGV scheme, PDN impedance near the signal TGV is reduced significantly at the resonance frequencies and as a result, the insertion loss of the TGV channel at these frequencies is reduced by more than 3 dB below 15 GHz. We also verify effectiveness of the proposed TGV scheme by simulating the eye diagram of the TGV channel at the data rate corresponding to the resonance frequency. By adopting the proposed grounding scheme, the eye opening is increased from 61.4% to 69.8% of the peak-to-peak voltage and the timing jitter is decreased from 5.3% to 4% of the one-unit interval. Also far-end crosstalk (FEXT) induced by the signal TGV to PDN noise coupling is suppressed from 19.5% to 1.8% of the input voltage. We verified the effectiveness of the ground TGV as a safer-return current path and shielding the crosstalk.
induced by the resonance. Without proper ground TGV design, coupled noise from the signal TGV to the glass interposer PDN propagates further due to the low loss of the glass substrate causing severe problems to the glass interposer channels and TGV channels.

II. Fabricated Glass Interposer Test Vehicles for the PDN Impedance and SI Measurements

Two test vehicles were designed and fabricated to measure and analyze the glass interposer PDN resonance effects on the high-speed TGV channel. The total of two glass interposer coupons were fabricated and each coupon includes several test vehicles with some of duplicated patterns to protect them from unexpected local cracks of the glass substrate developed during the fabrication processes. Freshly drawn glass itself is a very strong material but TGV and dicing processes generate defects in the glass that dramatically weaken the strength of the glass. Low-loss polymer is laminated on both side of the glass substrate to build up the metal layers and at the same time to prevent glass cracking [18], [19]. Even though polymer layers provide strength to the glass interposer, stress from metal layers may still cause the glass crack; therefore, we duplicated the designs to protect them from the cracks. Fig. 2 depicts the cross-sectional view and the design rules of the glass interposer fabricated. A total of four metal layers exist for the interposer channels and PDNs. Two metal layers are laminated on each side of the EN-A1 glass substrate to form the double sided interposers. Since copper used for plating metal layers is not adhesive to the glass substrate, additional low-loss polymer, ZS-100 is used between the glass substrate and the metal layers. Lamination of the low-cost and low-loss material layers is well-known technology to provide strength to the brittle substrate, which is also used in silicon interposers [20]. In the glass interposer, this low-loss polymer allows easy and reliable metallization with low-cost processes, minimizes direct moisture contact with the glass, and prevents glass cracks. To analyze the glass interposer PDN resonance effects on the signal/power integrity, we designed glass interposer test vehicles with TGV channels transitioning through power and ground planes. We targeted a scenario that TGV channels located far away from the ground and power TGVs. In the actual interposer, there exist many power/ground vias to operate the assembled chips. Designed glass interposer test vehicles also have several power/ground TGVs to form decoupling capacitor pads and to measure the PDN impedance, but these power/ground TGVs are located far-away from the signal TGVs; therefore, we can effectively analyze the glass interposer PDN resonance effects on the TGV channel. First, power/ground plane are designed in M2/M3 for all test vehicles. On the M1 and M4 layers, interposer channels are designed. Designed interposer channels include single-ended microstrip line patterns and crosstalk measurement patterns. To analyze the interposer PDN resonance loading effects on the signal channels, some channels include via transition structures. Fig. 2 depicts cross-sectional view of the TGV-transition structure in the designed glass interposer test vehicles. Channels on M1 and M4 are interconnected with microvias and TGVs.

The physical dimensions and material properties of the test vehicles are summarized in Table I. The height of the glass substrate is \(h_{\text{glass}}\) 100 \(\mu\)m and the thickness of the polymer layers 1 and 2 \((t_{\text{pol1}}, t_{\text{pol2}})\) are 22.5 and 17.5 \(\mu\)m, respectively. Each metal layer that consists of copper has thickness of 10 \(\mu\)m. The TGV diameter \((d_{\text{TGV}})\) and TGV pad \((d_{\text{pad-TGV}})\) are 120 and 90 \(\mu\)m, respectively. Due to the limitation associated with the process and design rules, microvias should be used and the diameter of the microvias \((d_{\text{pol-VIA}})\) and TGV pad \((d_{\text{pad-pol-VIA}})\) should be 45 and 75 \(\mu\)m, respectively. Relative permittivity of the glass substrate \((\varepsilon_{\text{glass}})\) and polymer \((\varepsilon_{\text{pol}})\) are 5.3 (at 2.4 GHz) and 3 (at 10 GHz), respectively, with loss tangent \((\tan \delta_{\text{glass}}, \tan \delta_{\text{pol}})\) of 0.004 (at 2.4 GHz) and 0.005 (at 10 GHz). The low loss of the glass substrate and polymer layer allows high-speed signaling up to tens of gigahertz range compared to the organic and silicon substrate but, at the same time, cause PDN resonance problems, which is reported in the previous study performed in the simulation level [16].

To analyze the glass interposer PDN resonance effects on the SI of the high-speed TGV channel, two test vehicles are measured in the frequency and time domain. Figs. 3(a) and 4(a) show the top view of the test vehicles and Figs. 3(b) and 4(b) show the cross-sectional view of the TGV channel.
Fig. 3. Test vehicle-A for measuring the glass interposer PDN resonance effects on insertion loss is shown. Top view of the test vehicle-A is shown in (a) that includes single ended high-speed interposer channels with and without TGV transitions. Insertion loss and eye diagram are measured for each channel for the comparison. Probing pad to measure the PDN impedance adjacent to the signal TGV is also located to compare insertion loss with PDN impedance. In the (b), cross-sectional view of the interposer channel with TGV transitions is shown.

The test vehicle described in Fig. 3(a) is designed and fabricated to measure the insertion loss and the eye diagram of the glass interposer channels and PDN impedance near the signal TGV. There are two interposer channels; one is designed on the top layer (M1) in the form of single-ended microstrip line with the line width of 50 μm and the length of 12 mm. The other is the single-ended microstrip line with TGV transitions. Channel lengths on M1 and M4 layers described as \( l_{M1} \) and \( l_{M4} \) are 2 and 8 mm, respectively. Channels on M1 and M4 are interconnected with TGVs and its cross-sectional view is depicted in Fig. 3(b). Insertion loss profiles in the frequency domain and eye diagrams in the time domain are measured with GSG-type microprobes. On M2 and M3, power and ground planes with 16 and 14 mm in the \( x \) and \( y \) directions were designed. 200 μm away from the signal TGV, a GS probing pad to measure the PDN impedance is designed. Each measuring pad is named with port numbers for easier comparison between graphs in next section.

The test vehicle described in Fig. 4(a) is designed and fabricated to measure the FEXT induced by the PDN resonance effects on FEXT induced by TGV to PDN noise coupling is shown. Top view of the test vehicle-B is shown in (a) that includes coupled high-speed interposer channels with and without TGV transitions. FEXT is measured in both frequency domain and time domain. In the (b), cross-sectional view of the interposer channel with TGV transitions is shown.

TGV transitions to compare the PDN resonance impacts on the TGV channels. The distance between coupled lines is 1.5 mm, which is much larger than the width of each line designed to be 50 μm. For the coupled channels with the TGV transitions, channel lengths on M1 and M4 layers described as \( l_{M1} \) and \( l_{M4} \) are set to be 4 mm each. These channels are measured with GSSG-type microprobes to provide 50 Ω termination to the other probing pads except for the pad where we measured FEXT. In the later sections, we use term T.V (test vehicle) A and B for the test vehicles shown in Figs. 3 and 4, respectively.

Fig. 5(a) shows photographs of the fabricated glass interposer coupons including Test vehicle-A and Test vehicle-B depicted in Figs. 3 and 4. There are several more glass interposer test vehicles, but in this study, we only used two among these test vehicles. In Fig. 5(a), test vehicles that we used for the measurement and analysis are shown inside the black-square. As mentioned earlier, we duplicated the same test vehicles in each coupon since cracks in the glass substrate can be generated during the fabrication processes, which might damage the test vehicles. Also to increase the fabrication yield, we included some dummy patterns. For the further studies, we also included some decoupling capacitor pads. In each test vehicle, we included eight decoupling capacitor pads with dimension of 3 mm × 1.8 mm. Each pad has six TGVs interconnecting the pad with power plane in
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Fig. 5. Two glass interposer coupons are designed and fabricated. Each coupon consists of several test vehicles shown in Figs. 3 and 4. From the glass interposer coupon shown in (a), test vehicles for the measurement of PDN resonance effects on the signal/power integrity are measured. (b) Test vehicles are measured using microprobes. (c) Glass interposer PDN impedances are measured at various locations. Decoupling capacitor pads, TGVs, and channels are marked.

M3. In Figs. 3 and 4, these dummy patterns and decoupling capacitor pads are neglected for easier understanding. Also, when we conducted simulation to suppress the glass interposer PDN resonance effects, these dummy patterns and pads are not included since including these in the 3-D-electromagnetic simulation will require tremendous amount of time and computational resources. Due to these reasons, we do not compare the measured and simulated result directly. However, these two results have very similar tendency in the frequency domain and the time domain. In this paper, we first measure the glass interposer test vehicles and analyze the glass interposer PDN resonance effects on high-speed TGV channel and verify the proposed resonance suppression scheme using simulation.

Fig. 5(b) and (c) shows photographs of the fabricated glass interposer coupons under the measurement. We used a microprobe (Picoprobe GSG, GSSG and GS type with 250 μm pitch, GGB industries Inc.), a calibration kit (#CS-9 and #CS-14, GGB industries Inc.), and coaxial cables (W.L. Gore & Associates, Inc.) for both time- and frequency-domain measurements. The frequency-domain measurements of glass interposer PDN impedance and channels are conducted up to 20 GHz using a vector network analyzer (VNA). The VNA, model N5230A from Agilent Technologies, has a bandwidth covering the frequency range from 300 kHz to 26.5 GHz. In the time-domain measurements, a pulse pattern generator (PPG) model MP-1763C from Anritsu and a digital sampling oscilloscope model TDS800B from Tektronix with bandwidth of 20 GHz are used.

In the following section, measurement results will be shown with analysis.

Fig. 6. Measurement result of test vehicle-A shown in Fig. 3. (a). Measured insertion loss of the glass interposer channels with and without TGV transitions is compared. (b) Measured insertion loss of the channel with TGV transitions is compared with the PDN impedance measured adjacent to the signal TGV. At the frequencies where high PDN impedance peaks are generated by the mode resonances, insertion loss of the glass interposer channel increased dramatically. Mode numbers of the resonance are marked in the parenthesis.

III. MEASUREMENT AND ANALYSIS OF THE GLASS INTERPOSER PDN RESONANCE EFFECTS ON A HIGH-SPEED TGV CHANNEL

In this section, effects of the glass interposer PDN resonance on the high-speed TGV channel are measured and analyzed. In the previous studies, these issues in glass interposers are reported only in the simulation level. We first verified these effects by measuring the actual glass interposer test vehicles fabricated.

A. Measurement and Analysis of the Glass Interposer PDN Resonance Effects on the Insertion Loss and Eye Diagram of the High-Speed TGV Channel

In Fig. 6, measured insertion losses of the glass interposer channels and the PDN impedance are compared. Test vehicle-A is measured. The measured insertion losses of the glass interposer channel with and without TGV transitions are shown in Fig. 6(a). Up to 20 GHz, insertion loss profile is similar for both channels, but at certain frequencies, insertion loss dramatically increased in the channel with TGV transitions. This phenomenon can be explained by analyzing the graph shown in
Fig. 6(b) that compares the measured insertion loss of the channel with TGV and the PDN impedance measured adjacent to the signal TGV. The PDN impedance adjacent to the signal TGV has low impedance up to 20 GHz; therefore, the power/ground plane is a good return path except at the resonance frequencies. When the signal TGVs are located far-away from the ground TGVs, displacement current flows between the power and the ground planes to form a return current path. As frequency increases, glass interposer PDN inductance also increases affecting the return current path. Also, the dielectric loss increases as frequency increases; therefore, the loss of the TGV channels also increases. However, in the glass interposer, return current is more severely affected by the mode resonances than other PDN factors. At the mode resonance frequencies wherein high PDN impedance peaks (higher than the PDN impedance determined by the PDN inductance) are generated, return current of the channel is affected more severely since high impedance PDN takes more power than the receiver. Low loss of the glass substrate (high Q-factor) generates sharp PDN impedance peaks affecting the return current of the TGV channel. The magnitude of these impedance peaks is determined by the loss tangent of the glass substrate. Due to this reason, return current is discontinued and the insertion loss increased significantly for the channel with TGV transitions at the resonance frequencies. At these frequencies, signal quality at the receiver side is expected to be degraded. Appearance of high impedance peaks at these frequencies depends on the size of the PDN, locations of the signal TGV, and material properties of the glass substrate and polymer. Therefore, if we measure TGV channels’ insertion loss or PDN impedance at other locations, different insertion loss profiles and impedance properties will be obtained.

Eye diagrams are measured to verify this glass interposer PDN resonance loading effect on the interposer channel with TGV as shown in Fig. 7. Eye diagrams of the glass interposer channel with and without TGV transitions are measured. The generated data pattern from PPG is a pseudo-random-binary-sequence (PRBS) of $2^8 - 1$, with a rise-and-fall time of 30 ps and data rate of 7880 Mbps, which corresponds to PDN’s (1, 0) mode resonance frequency. Fig. 7(a) shows the eye diagram of interposer channel without TGV transitions. The eye-opening voltage and timing jitter are 362.2 mV (72.4% of the peak-to-peak voltage) and 18.4 ps (14.5% of 1UI) at 7880 Mbps. Fig. 7(b) shows the eye diagram of interposer channel with TGV transitions. The eye-opening voltage and timing jitter are 291.9 mV (58.4% of the peak-to-peak voltage) and 24.4 ps (19.2% of 1UI) at 7880 Mbps. At the resonance frequency, signal quality is degraded both in the frequency domain and the time domain.

B. Measurement and Analysis of the FEXT Induced by the Signal TGV to PDN Noise Coupling at the Glass Interposer PDN Resonance Frequencies

We also measured FEXT in the frequency domain and the time domain. Test vehicle-B shown in the Fig. 4(a) was measured. First, we measured coupling parameters of coupled channels with and without TGV transitions in the frequency domain. We also measured PDN impedance from the probing pad of the test vehicle-B defined as port 9. Frequency-domain measurement results are plotted in Fig. 8. The distance between coupled channels in the test vehicle-B is much larger than the channel width; therefore, it is less vulnerable to the crosstalk issues. In Fig. 8(a), FEXT in the frequency domain is compared for the coupled interposer channels with and without TGV transitions. Also, in Fig. 8(b), PDN impedance measured near the signal TGV is plotted. By comparing the coupled parameter of channels with TGV transition ($S_{xy}$ of test vehicle-B) and PDN impedance measured near the signal TGV ($Z_{pp}$ of test vehicle-B), we can conclude that for the channel with signal TGV transition, due to the high PDN impedance at the mode resonance frequencies, return current discontinuity occurs and this captured return current propagates along the PDN. This captured return current in the PDN can be coupled to the other channels inducing crosstalk problems.

We also validated this FEXT induced by the PDN resonance effect in the time domain. This result is shown in Fig. 9. We injected 7940 Mbps clock signal (0 to 1 V, 30 ps rise-and-fall time and all ports terminated with 50 Ω) that corresponds to the (1, 0)/(0, 1) mode resonance frequency of the test
Fig. 8. Measurement result of test vehicle-B shown in Fig. 4. (a) Measured FEXT of interposer channels with and without TGV transitions is compared in the frequency domain. More FEXT is induced to the adjacent channel due to the resonances in the case of channel with TGV transitions. (b) PDN impedance measured near the signal TGV is shown. At the frequencies where high impedance peaks occur, coupling also increased.

Fig. 9. Measured FEXT in the time domain for the TGV channel at the resonance and nonresonance frequency is shown. At the resonance frequency, more noise is induced to the adjacent channel.

IV. SUPPRESSION OF THE GLASS INTERPOSER PDN RESONANCE EFFECTS ON THE HIGH-SPEED TGV CHANNEL

As mentioned in the previous section, glass interposer PDN serves as a good return current path. However, at the glass interposer PDN resonance frequencies, many problems occur and these issues are measured and analyzed. One of the most well-known resonance suppression methods is ground design that suppresses resonance effects and decoupling capacitor schemes, which control the PDN impedance [21]–[23]. However, current glass interposer design rules limit the effectiveness of the decoupling capacitors due to large pad design [16]. In this section, the effectiveness of proposed ground TGV design on the glass interposer PDN resonance suppression is validated in the simulation level. In Fig. 10, the proposed grounding scheme to suppress the resonance effects is shown. The same structures and materials are used that were mentioned in Figs. 3 and 4 except that we have also added two ground TGVs, 200 μm away from the signal TGVs for the channels with TGV transitions, which are vulnerable to the PDN resonances. These ground TGVs serve as return current path and noise shield for the TGV channels. For the simulation simplicity, we ignore some dummy pads and vias placed for safer fabrication of the test vehicles. Due to these reasons, simulation and measurement data show some difference in value; however, almost identical electrical characteristics are maintained. We also placed package ground underneath the glass interposer. Ground balls underneath the glass interposer interconnect ground TGVs with the package ground. In Fig. 10(b), cross-sectional view near the signal TGV is depicted. We now use term “TGV-shielded test vehicle” for the TGV channels with the proposed grounding scheme.

We verify the effectiveness of the proposed grounding scheme on resonance effects suppression by simulating the insertion loss, PDN impedance near signal TGV, and eye diagram. We also simulate FEXT in the frequency domain and the time domain. In vehicle-B’s PDN to the coupled channel with TGV transitions. 53-mV (5.3% of the input voltage) FEXT voltage is measured. This value is 10 times larger than the case when we injected 10,000 Mbps clock signal which is nonmode resonance frequency to the same coupled channels.

We can conclude that PDN resonance of the glass interposer generates high impedance peaks and this high impedance peaks cause many SI/PI issues. When there are signal via transitions using TGVs, high impedance peaks generated by the interposer PDN mode resonances disconnect return current path of the channel at certain frequencies. Therefore, return current is loaded in the PDN, increasing the channel loss, degrading eye diagram, and inducing PDN noise causing crosstalk to the adjacent channels. To fully take the advantages of the glass listed in Section I, design that could suppress these PDN resonance effects on TGV channels is necessary. In the following section, we propose grounding scheme that provides return current path less vulnerable to the glass interposer PDN resonance and that shields noise coupling. We validate the effectiveness of the suggested grounding scheme using the full 3-D-EM simulator, Ansys HFSS.
the simulation level, we verify the effectiveness of the proposed ground TGV shielding for the glass interposer channel operating at the data rate of the high-bandwidth memory (HBM) channel from the FEXT induced by the PDN resonance.

A. Effectiveness of the Proposed Shielded-TGV Design on the PDN Impedance, Insertion Loss of the TGV Channel, and the Eye Diagram of the High-Speed TGV Channel

To verify the effectiveness of the proposed ground TGV design on the insertion loss of the channel, we simulated and compared interposer channels including TGV transitions with and without the proposed grounding scheme. In Fig. 11(a), insertion losses of channel with and without proposed grounding scheme are compared. Frequency range under 15 GHz, placing ground TGVs lowered the insertion loss at the resonance frequencies since the return current path is less affected by the PDN. This can be clearly explained by comparing the PDN impedance seen near the signal TGV, which is shown in Fig. 11(b). Frequency range below 15 GHz, PDN impedance is lowered at the mode resonance frequencies by placing the ground TGVs. Due to the additional ground TGVs, via clearance and the package ground underneath the glass interposer, mode resonance frequencies are shifted slightly. Even though there are some shifts in the resonance frequencies, values of the PDN impedance peaks are lowered significantly by placing the ground TGVs. Due to this reason, in some frequencies, insertion loss is decreased more than 3 dB.

We also simulated eye diagram to verify the effectiveness of the proposed ground TGV design on the resonance suppression in the time domain. S-parameter touchstone files are extracted from the insertion loss and PDN impedance simulation setups. We have injected PRBS signal with data rate of 9414 Mbps and 30ps rise-and-fall time that corresponds to PDN’s (1, 0) mode resonance frequency. Both channels have the same dimension with TGV transitions, which is shown in Fig. 3(a), but the only difference is the existence of the ground TGVs near the signal TGVs and the package ground. In Fig. 12, simulated eye diagrams are compared. Fig. 12(a) is simulated eye diagram of the TGV channel without the proposed ground design. The eye-opening voltage and timing jitter are 307 mV (61.4% of the peak-to-peak voltage) and 5.64 ps (5.3% of the 1-unit interval) with the input of PRBS signal with data rate of 9,414 Mbps. Fig. 12(b) is simulated eye diagram of the TGV channel with the proposed ground design. The eye-opening voltage and timing jitter are 349 mV (69.8% of the peak-to-peak voltage) and 4.27ps (4.0% of the 1-unit interval) with the input of PRBS signal with the data rate of 9,414 Mbps. As can be seen...
from the insertion loss profile in the frequency domain, at this frequency (4.707 GHz), which corresponds to the injected data rate (9,414 Mbps), insertion loss is lowered 3.78 in dB scale by adopting the suggested ground design.

Due to this reason, eye opening is increased and the timing jitter decreased. Placing the proposed ground TGV design to provide that return current paths are less affected by the PDN resonance lowered PDN impedance near signal TGV and improved performance of the interposer channel both in the frequency domain and the time domain.

**B. Effectiveness of the Proposed Shielded-TGV Design on the Suppression of FEXT Induced by the PDN Resonance**

We also proved the effectiveness of the proposed ground TGV design on the FEXT induced by the glass interposer PDN resonance. As mentioned in the previous section, the distance between coupled channels is set to be 1.5 mm; therefore, ground TGVs can be located between coupled channels’ signal TGVs since the TGV pitch is set to be 200 μm. We simulated FEXT between coupled TGV channels shown in Fig. 4(b) with and without the proposed ground TGV design. In Fig. 13(a), comparison of the FEXT in the frequency domain is shown. Compared to the measurement result shown in Fig. 8(a) with dotted-line, simulated FEXT result is larger than the measured FEXT in the frequency domain; however, the tendency of sudden increase in FEXT at mode resonance frequencies is maintained. As can be seen in Fig. 13(a), suggested ground TGV design lowered FEXT in the frequency range under 15 GHz. When the TGV channels are designed without ground TGVs, return current is kept in the PDN at the mode resonance frequencies due to the high PDN impedance. This return current held in the PDN can be regarded as a PDN noise, which is a source of the FEXT. In the frequency domain, we verified the effectiveness of the ground TGV design on FEXT reduction in the simulation level.

Using the S-parameter extracted from the frequency-domain simulation, noise coupling in the time domain is also conducted, which is shown in Fig. 13(b). 8,826 Mbps clock signal (0 to 1 V,
30 s rise-and-fall time, and all ports terminated with 50 Ω) that corresponds to the (1, 0)/(0, 1) mode resonance frequency is injected. Coupled channel without ground TGVs, 195 mV (19.5% of the input voltage) FEXT voltage is induced. This simulated FEXT value in the time domain is larger than the measured result since more coupling in the frequency domain is obtained in the simulation. Since the time-domain simulation is based on the S-parameters extracted during the frequency-domain simulation, this tendency is also reflected in the time-domain simulation. By placing the proposed ground TGV design to the couple TGV channel, FEXT voltage induced to the victim is channel reduced to 18 mV which is 1.8% of the input voltage. Coupled TGV channel with proposed ground TGVs suppressed FEXT voltage induced by the PDN resonance to 10% of the coupled TGV channel without ground TGVs.

To analyze how severe FEXT induced by the PDN resonance on the glass interposer channel is and to verify the effectiveness of the suggested ground TGV for shielding this FEXT, we simulated eye diagram of the TGV channel with the data rate of 2 Gbps that corresponds to that of HBM channel and 8,826 Mbps clock signal as an aggressor. Results are shown in Fig. 14. We used same setup and the port configuration of the test vehicle-B [see Fig. 4(b)].

We injected PRBS of $2^8 - 1$, 0 to 1.2 V with rise-and-fall time of 30 ps and the data rate of 2 Gbps to the port 7 as an input signal. As an aggressor, 8,826 Mbps clock signal (0 to 1 V, 30 s rise-and-fall time and all ports terminated with 50 Ω) that corresponds to the (1, 0)/(0, 1) mode resonance frequency was injected. Port 6 is terminated with 50 Ω and port 8 where we monitor the received eye diagram is terminated with 2-pF capacitor. This input data and receiver condition correspond to those of HBM channel [24], [25]. Eye diagram of the TGV channel without aggressor is shown in Fig. 14(a) as a reference. Since 2 Gbps input data rate is nonmode resonance frequency and due to low loss characteristics of the TGV channel, eye opening is 90.4% of the peak-to-peak voltage and timing jitter is 2.02% of 1UI. However, when we injected clock signal as an aggressor, received eye diagram is deteriorated severely due to FEXT. Since the distance between two coupled channels is much larger than the width of the channel, we can conclude that this FEXT is induced from signal TGV to PDN and then PDN to the channel due to the glass interposer PDN resonance. This result is shown in Fig. 14(b). Compared to the eye diagram shown in Fig. 14(a), eye opening is reduced to 81.4% of the peak-to-peak voltage from 90.4% of the peak-to-peak voltage. Also timing jitter is increased to 7.68% of 1UI from 2.02% of 1UI. Effectiveness of the proposed ground TGV design for shielding the FEXT caused by the glass interposer PDN is shown in Fig. 14(c). By applying the proposed ground TGV design to the TGV channels, FEXT is mostly shielded. This can be validated by comparing the eye diagrams shown in Fig. 14(a) and (c). The proposed ground TGV design almost eliminated FEXT issues caused by the glass interposer PDN resonance.

We have verified the effectiveness of the proposed ground TGV design on the PDN resonance suppression by analyzing the simulated insertion loss, PDN impedance, eye diagram, and FEXT. Even though placing ground TGVs near the signal TGVs
may limit rout ability in the glass interposers, due to the PDN resonance problems associated with the low loss of the glass substrate, ground TGV design seems inevitable in glass interposers. Considering current design rules of the glass interposer, ground TGV design that can suppress the resonance effects regardless of the position is one of the most promising solutions to the glass interposer PDN resonance problems. In the actual interposers, such as HBM modules, there exist five to six metal layers for the signal, power, and ground nets [25]. If the glass interposer is adopted in the systems for low-cost and high-density layers for the signal, power, and ground nets [25], the PDN resonance problems associated with the glass interposer PDN resonance, glass interposer technologies can surely achieve both the superior electrical performances and significant cost reduction at the same time.

V. CONCLUSION

In this paper, the glass interposer PDN resonance effects on a high-speed TGV channel are measured and analyzed for the first time. Although glass interposer PDN serves as a good return current path, due to the low loss of the glass substrate, sharp PDN impedance peaks are generated at the mode resonance frequencies. These high impedance peaks cause the return current discontinuity, which can result in the increased insertion loss when there exist signal reference changes using TGVs. The measured eye diagram of the channel with signal TGV transitions has smaller eye-opening voltage and larger timing jitter at the data-rate corresponding to the resonance frequency, compared to those of the channel without any signal TGV transition. Furthermore, we measured the PDN resonance effects on the FEXT in the frequency domain and the time domain. For the coupled channels, more FEXT was induced at the resonance frequencies. Without PDN resonance suppression, the performance of the system based on the glass interposer could be severely degraded.

For PDN resonance suppression, we proposed a grounding scheme including ground TGVs adjacent to the signal TGVs and package ground. By applying the proposed grounding scheme, in the simulation level, we suppressed PDN impedance near the signal TGV and as a result, the insertion losses of the channel at the resonance frequencies were suppressed below 15 GHz, with the maximum reduction of 3.78 dB. Also, by applying the proposed design, the eye diagram at the resonance data rate was greatly improved: The eye height was increased from 61.4% to 69.8% of the peak-to-peak voltage and the timing jitter decreased from 5.3% to 4% of the one-unit interval. In the case of FEXT, the coupled voltage was reduced to 10% compared to the TGV channel without the ground TGVs. Therefore, when designing glass interposer PDN and channels, a proper ground TGV design is crucial.

2.5-D integration based on glass interposers is a potential means of achieving high-bandwidth and high-integration density electrical systems with reduced manufacturing cost. In order to take advantages of glass interposers, PDN resonance should be carefully suppressed. For this reason, the measurement-based analysis of the glass interposer PDN and TGV channels, as well as the PDN resonance suppression method using ground TGV, provide useful design guidance for the glass interposer PDN and TGV channel. By mending these SI/PI problems associated with the glass interposer PDN resonance, glass interposer technologies can surely achieve both the superior electrical performances and significant cost reduction at the same time.

REFERENCES


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