Abstract: In this paper, for the first time, an accurate glass package power distribution network (PDN) model is proposed for the PDN impedance estimation based on a segmentation method. To verify the proposed modeling method, glass package test vehicles including the PDN are fabricated. Estimated impedance of the glass package PDN based on proposed model is validated by comparing measured and simulated glass package PDN in the frequency domain up to 20 GHz. Estimated impedance based on proposed modeling method showed good correlation with measurement and 3-Dimensional electromagnetic (3D-EM) simulation. Compared to 3D-EM simulation, the proposed method is fast but accurate. Due to low loss of the glass package substrate, sharp PDN impedance peaks at mode resonance frequencies are generated. Signal and power integrity degradation at these frequencies are analyzed. Using the proposed modeling method, locations and frequencies where signal TGVs are less affected by the PDN mode resonances can be efficiently estimated for early stage package PDN design and signal TGV floor plan.

Key Words: glass package, power distribution network (PDN), power noise, resonance, segmentation method

1. Introduction
Recent technology trends require realization of high-speed electrical systems with wider bandwidth, superior electrical performances, smaller dimensions and lower manufacturing cost. Due to technical difficulty in transistor scaling associated with sub-ten nano-meter (nm) physical dimension of the...
transistor gate length, 2.5-Dimensional (2.5-D) system integration based on through silicon via (TSV) and silicon packaging using ultra-thin packages and interposers have attracted substantial attention as a promising solution toward current industrial challenges due to their improved electrical performances and compact design [1–4]. The 2.5-D integration provides much shorter channel and interconnection length compared to the conventional, lateral integration (2-D integration). Also, the 2.5-D integration based on silicon packaging dramatically increases integration density of integrated circuits (ICs) and the number of channels since it allows ultra-fine pitch metalization [5]. Because of these merits, 2.5-D integration based on both TSV and silicon packaging technology enables the system to transmit a larger amount of data simultaneously through short TSV and interposer channels which can increase the system bandwidth significantly [6]. As a result, high bandwidth memory (HBM) which is in form of 2.5-D ICs was introduced and widely adopted in graphic modules where terabyte per second (TB/s) bandwidth is needed [7].

Even though the 2.5-D integration based on silicon packaging provides promising solutions toward industrial challenges, in long term, silicon packaging is expected to suffer from high manufacturing cost and limited wafer dimension related to yield. Also due to the conductivity of the silicon substrate, a high-speed transmitted signal is degraded which causes significant signal integrity (SI) issues [8]. Because of these reasons, industries are developing alternative ultra-thin package substrate materials which are also suitable for fine-pitch metalization compatible to silicon. Among many materials, glass as a package substrate material was proposed as a superior alternative of silicon. The glass package substrate has 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 ultra-thin panel sizes compared to that of silicon wafers and more importantly, excellent electrical resistivity of glass substrate which will contribute to low signal loss up to GHz range [9]. Therefore 2.5-D integration based on glass package is a potential means of achieving high-bandwidth and high-integration density electrical systems at the same time lowering the manufacturing cost.

The glass package consists of low loss glass substrate, polymer layers, through glass vias (TGVs) and fine-pitch metals for designing signal channels and power distribution networks (PDNs) on both sides thin glass substrate. Like other semiconductor packages, there exist PDN in the glass package to supply stable power to the assembled ICs. Low loss of the glass substrate enables high-speed signaling. However, low loss of the package substrate generates sharp PDN impedance peaks at the PDN resonance frequencies which affect return current of the channel with through vias, increasing insertion loss, cross-talks and generating PDN noise coupling [10–14]. These studies were conducted in organic packages and 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 package [15]. Therefore, it is important to estimate PDN impedance properties of the glass package not only to analyze impedance itself but also to estimate locations and frequency ranges affected by the PDN mode resonance. Figure 1(a) shows the degradation of the signal and power integrity in the glass package due to the PDN resonance. However, based on conventional electromagnetic (EM) simulator, it takes long simulation time and large computational resources to estimate PDN impedance profiles and mode resonance frequencies of the glass package due to aspect-ratio difference described in Fig. 1(b). Also, accurate and efficient PDN models are crucial, since characteristics of non-linear power/ground noise generated by simultaneously switching output (SSO) buffers are heavily dominated by the package PDN impedance, especially around anti-resonance frequency where high impedance peak is generated.

In this paper, for the first time, an accurate glass package power distribution network (PDN) model is proposed for the PDN impedance estimation based on a segmentation method. To verify the proposed modeling method, glass package test vehicles including the PDN are fabricated. Estimated impedance of the glass package PDN based on proposed model is validated by comparing measured and simulated glass package PDN in the frequency domain up to 20 GHz for the first time. Estimated impedance based on proposed modeling method showed good correlation with measurement and simulation even at mode resonance frequencies where wave properties dominate the PDN impedance characteristics. At the mode resonance frequencies, depending on the location in the PDN, impedance
peaks may not appear. The proposed modeling method showed good correlation with measurement and simulation even the monitoring location in the PDN is changed. Lastly, impact of the glass package PDN resonance on signal integrity is analyzed based on measurement and simulation in the frequency-domain and the time-domain. When the signal TGV is affected by the PDN impedance mode resonance, return current of the TGV channel is loaded in the PDN causing various signal and power integrity issues. Using the proposed modeling method, locations and frequencies where signal TGVs are less affected by the PDN mode resonances can be efficiently estimated at the preliminary package design stage.

![Degradation of the signal and power integrity in the glass package due to the PDN resonance is depicted.](image1)

(a) Degradation of the signal and power integrity in the glass package due to the PDN resonance is depicted. To avoid resonance effects, estimation of the PDN impedance in the glass package is important. (b) Due to aspect ration difference in the glass package, long simulation time and large computational resources are needed to estimate the PDN impedance using EM simulators.

### 2. Proposal of glass package power distribution network (PDN) modeling based on a segmentation method

In this section, a new glass package PDN modeling based on a segmentation method is proposed. First, concept of the segmentation method is explained. To apply the segmentation method, precise unit cell modeling which compose whole glass package PDN is needed. The unit cell is modeled based on RLC-lumped model, especially, dielectric constants of the glass substrate and build-up polymer layers are modeled into a single complex dielectric constant to consider loss of the dielectric mixture. As with the distributed RLC lumped model based on scalable equations with structural and material parameters, the proposed modeling provides both physical and material insights into the effects of altering the PDN parameters.

#### 2.1 Concept of a segmentation method

A segmentation method is used for the estimation of the impedance properties of the PDN. Using the segmentation method, impedance of desired structure can be estimated efficiently without using the circuit simulators or 3D-EM simulators. A basic concept of the segmentation method is shown in Fig. 2. In order to calculate the impedance of the whole PDN structure, total structure is decomposed into repeating independent structures, which are unit cells. After calculating the impedance matrices of each unit cell, impedance matrix of the total structure is calculated using the segmentation method and boundary conditions [16].
Fig. 2. A basic concept of the segmentation method is depicted. Impedance matrix of the total structure can be estimated using the impedance matrices of the two independent structures (Unit Cells).

Using the segmentation method, impedance of the whole PDN can be derived from the decomposed PDN structure 1 and 2 as shown in Fig. 2. The impedance properties of the PDN structures are derived with an impedance-matrix form as shown in Eqs. (1) and (2)

\[
\begin{bmatrix} V_a \\ V_p \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ap} \\ Z_{pa} & Z_{pp} \end{bmatrix} \begin{bmatrix} I_a \\ I_p \end{bmatrix}
\] (1)

\[
\begin{bmatrix} V_b \\ V_q \end{bmatrix} = \begin{bmatrix} Z_{bb} & Z_{bq} \\ Z_{qb} & Z_{qq} \end{bmatrix} \begin{bmatrix} I_b \\ I_q \end{bmatrix}
\] (2)

After applying the boundary condition shown in the Fig. 2, impedance matrices of the PDN structure 1 and 2 are integrated into the impedance matrix of the total structure as presented in Eq. (3).

\[
\begin{bmatrix} V_a \\ V_b \end{bmatrix} = \begin{bmatrix} Z_{ba} - Z_{ap}(Z_{pp} + Z_{qq})^{-1}Z_{pa} & Z_{ap}(Z_{pp} + Z_{qq})^{-1}Z_{qb} \\ Z_{bbq}(Z_{pp} + Z_{qq})^{-1}Z_{pa} & Z_{bb} - Z_{bq}(Z_{pp} + Z_{qq})^{-1}Z_{qb} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \end{bmatrix}
\] (3)

Consequently, impedance of the total structure can be derived by using the impedance matrix of the independent structures and the segmentation method. In order to obtain accurate result, impedance matrix of the independent structure should be modeled precisely. For silicon package PDN, due to process limitation associated with CMOS design rules, PDN must be designed in form of mesh or grid. In such case, even unit cell should be divided into multiple sections [17, 18]. However, power and ground metal planes can be fabricated in the glass package and as a result, PDN of the whole glass package can be modeled by single unit cell similar to organic package [19]. In the following subsections, designed glass package PDN structure is described and unit cell model which composes the glass package PDN is proposed.

2.2 Design of the glass package PDN and unit cell

Glass package PDN is designed and fabricated to verify the proposed modeling method. In Fig. 3, the designed glass package PDN is depicted. As can be seen from Fig. 3(a), whole PDN consists of repetitive unit cell depicted in Fig. 3(b). In the glass package designed, a total of four metal layers for signal channels and PDNs exist. In Fig. 3(c), cross-sectional view of the TGV in the probing pad is depicted. Two metal layers are laminated at the top and bottom of the EN-A1 glass substrate to form the double-sided glass package. Since copper used to form metal layers is not adhesive to the glass substrate, additional low loss polymer layers (material: ZS-100) is used between the glass substrate...
and the metal layers. These low-loss polymer layers provide mechanical strength to the glass package; prevent glass substrate cracking and moisture contact to the substrate [20,21].

Power and ground planes which compose the glass package PDN are designed in M2 and M3 layer for modeling and analysis of the glass package PDN. In M1 and M4 layer, signal channels and probing pads are designed for analysis of glass package PDN resonance effects on the signal/power integrity and measurement for model validation. As can be seen from the Fig. 3(a), probing pads exist on M1, the top layer. Since power plane is designed in M2 layer, which is below M1 layer, micro-via is used to interconnect power pads in M1 layer and power plane in M2 layer. In case of ground pads, through glass vias (TGVs) are used to interconnect ground pads in M1 and ground plane in M3.

The physical dimensions and material properties of the designed glass packages are summarized in Table I. The height of the glass substrate (h), the thickness of the polymer layer 1 and 2 (t_{p1}, t_{p2}) and metal layer thickness (t_m) are summarized. The TGV diameters (d_{TGVP} and d_{TGVB}) and TGV pad (d_{TGVPad}) are 60 \mu m for top, 40 \mu m for bottom, and 90 \mu m respectively. Due to the limitation associated with the process and design rules, micro-via should be used and the diameter of the micro-
via \(d_{\mu}\) and micro-via pad \(d_{\mu\text{pad}}\) are 45 \(\mu m\) and 75 \(\mu m\) respectively. Lateral dimensions of the whole PDN in x and y directions are described with the parameters, \(l_x\) and \(l_y\) both 12 \(mm\). In this study we assumed the unit cell dimensions in x and y directions equally \((l_u)\), which should be smaller than the wavelength over 20 \((\lambda/20)\). This can be calculated from the target frequency and the real term of the effective dielectric constant which will be described in detail.

Relative permittivity of the glass substrate \((\varepsilon_g)\) and polymer \((\varepsilon_p)\) are 5.3 (at 2.4 GHz) and 3 (at 10 GHz) respectively with loss tangent \((\tan\delta_g, \tan\delta_p)\) of 0.004 (at 2.4 GHz) and 0.005 (at 10 GHz). Low loss of the glass substrate and polymer layer allows high-speed signaling up to tens of GHz range compared to the organic and silicon substrate, but at the same time causes PDN resonance problems which is reported in the previous study performed in simulation level [15]. Therefore, to determine proper locations of the signal TGV, fast and accurate PDN impedance estimation model is crucial in the glass package.

| Symbol | Value |
|--------|-------|
| \(h\)  | 100 \(\mu m\) |
| \(t_{p_1}\)  | 22.5 \(\mu m\) |
| \(t_{p_2}\)  | 17.5 \(\mu m\) |
| \(t_m\)  | 10 \(\mu m\) |
| \(d_{TGV_T}\)  | 60 \(\mu m\) |
| \(d_{TGV_B}\)  | 40 \(\mu m\) |
| \(d_{\mu}\)  | 45 \(\mu m\) |
| \(d_{\mu\text{pad}}\)  | 75 \(\mu m\) |
| \(l_x\)  | 12 \(mm\) |
| \(l_y\)  | 12 \(mm\) |
| \(l_u\)  | varies |
| \(\varepsilon_g\)  | 5.3 @ 2.4 GHz |
| \(\varepsilon_p\)  | 3.0 @ 10 GHz |
| \(\tan\delta_g\)  | 0.004 @ 2.4 GHz |
| \(\tan\delta_p\)  | 0.005 @ 10 GHz |
| \(\sigma_m\)  | 5.8 \(\times 10^7\) \(\sigma/m\) |

**Table I.** Physical Dimensions and Material Properties of the Designed and Fabricated Glass Package PDN.

### 2.3 Glass package PDN unit cell modeling for a segmentation method

The segmentation method, which is based on a \(z\)-parameter matrix calculation, is a well-known method for the impedance estimation of a whole PDN using a single or multiple unit cells [16–18]. Applying the segmentation method to the unit cell shown in Fig. 3(b), the PDN impedance of the whole structure can be estimated. To accurately estimate the impedance of the glass package PDN, precise modeling of the unit cell is crucial. The unit cell can be modeled by calculating the resistance \((R)\), inductance \((L)\) of the PDN and complex capacitance \((C)\) which includes the conductance of the dielectrics between power and ground planes. In Fig. 3(c), probing pad model which must be designed and fabricated for experimental validation of the proposed segmentation method is depicted.

First, effective dielectric constant should be determined to calculate the dimension of the unit cell, \(l_u\) which is used to calculate other PDN parameters. There are three dielectric material layers between power and ground, polymer under and above the power and ground plane and the glass substrate in the middle. In order to define the dimension of the unit cell, these dielectric layers should be modeled into equivalent dielectric mixture layer. In Fig. 4, modeling of the dielectric layers into a single dielectric mixture layer is depicted. In most EM simulators, meshes will be automatically assigned between dielectric layers. Therefore, we do not have to consider dielectric modeling when using the EM simulation except for special cases. However, for the segmentation method which is
Fig. 4. Modeling of the dielectric layers into single dielectric mixture to calculate the dimension, capacitance and conductance of the unit cell of the glass package PDN is depicted.

Based on Z-parameter calculation, accurate unit cell modeling which is crucial since small error can be accumulated causing inaccurate results. Since the polymer, ZS-100 has very low loss ($\tan\delta_p = 0.005$ at 10 GHz) and thinner than the glass substrate, we assumed that the conductivity of the polymer layer is close to zero to simplify the calculation. This assumption is similar to an assumption used in a research related to charge polarization phenomenon which was first studied by Maxwell who considered a two-phase system with one of the phases insulating [22]. By applying this assumption, frequency dependent complex dielectric constant of the polymer can be written as Eq. (4). Also the complex dielectric constant of the glass substrate is written in Eq. (5).

$$\epsilon_p(\omega) = \epsilon_p + \frac{\delta_p}{j\epsilon_0\omega} \approx \epsilon_p \quad (\delta_p = 0)$$  \hspace{1cm} (4)

$$\epsilon_g(\omega) = \epsilon_g + \frac{\delta_g}{j\epsilon_0\omega}$$  \hspace{1cm} (5)

Using this assumption, the dielectric layers can be modeled in to single dielectric mixture layer represented with the effective complex dielectric constant, $\epsilon_{mix}(\omega)$ shown in Eq. (6) [23].

$$\epsilon_{mix}(\omega) = \epsilon_{mix,real} + \frac{\Delta \epsilon}{1 + j\omega \tau}$$  \hspace{1cm} (6)

where $\Delta \epsilon$ is the dielectric strength of the inter-facial polarization and $\tau$ is the relaxation time of the polarization. This expressions are summarized in Eqs. (7) and (8) where $q$ is the volume fraction of the dielectric layers and $\epsilon_{mix,real}$ is the real term of the complex dielectric constant of the dielectric mixture which is summarized in Eq. (9).

$$\Delta \epsilon = \frac{q \epsilon_p \epsilon_{mix,real}}{(1 + q)\epsilon_g}$$  \hspace{1cm} (7)

$$\tau = \frac{q(\epsilon_p + \epsilon_g) + \epsilon_g}{(1 + q)\delta_g}$$  \hspace{1cm} (8)

$$\epsilon_{mix,real} = \frac{\epsilon_p \epsilon_g (1 + 2q)}{q(\epsilon_p + \epsilon_g) + \epsilon_g}$$  \hspace{1cm} (9)

Throughout Eqs. (4) to (9), it is assumed that the polymer layer is insulating ($\delta_p = 0$), since the thickness of the polymer layer is thinner than that of the glass substrate and the polymer layer also has small loss. If the thickness of the polymer layer is increased, the loss of the polymer layer must be considered. It is possible to consider loss of the polymer layer, which is shown in Eq. (10). However, by using the simplified equation shown in Eq. (6) which is based on the assumption, it is possible to calculate $\epsilon_{mix,real}$ more easily which is important parameter to determine the dimension of the unit cell.
\[ \epsilon_{\text{mix}}(\omega) = \frac{\epsilon_p(\omega)\epsilon_g(\omega)}{q_p(\omega) + (1-q)\epsilon_g(\omega)} \]  

The dimension of unit cell \( l_u \) can be set smaller than the wavelength over 20 (\( \lambda/20 \)) summarized in Eq. (11) where \( c \) is the speed of the light in the air.

\[ l_u < \frac{\lambda}{20} = \frac{c}{20f_{\text{max}}\sqrt{\epsilon_{\text{mix,real}}}} \]  

When the dimension of the unit cell, \( l_u \) is determined, capacitance (\( C \)) between power and ground plane in the unit cell can be calculated using Eq. (6) and physical parameters. Advantage of using Eq. (6) is that conductance of the dielectric mixture can be automatically included in the capacitance of the unit cell. Even though the conductance of the unit cell is expected to be small since the loss tangent of the polymer and glass are very low, it is important to calculate the parameters as accurate as possible since small error can be accumulated which will result in inaccurate PDN impedance properties when using the segmentation method. The capacitance of the unit cell is shown in Eq. (13).

\[ C = \epsilon_0 \epsilon_{\text{mix}}(\omega) \frac{l_u^2}{t_{\text{total}}} \]  

Unit inductance of the unit cell which is shown in Eq. (13) can be calculated from the air-filled capacitance, \( C_{\text{air}} \) shown in Eq. (14). In Eq. (15), Unit resistance of the unit cell is shown. In summation of resistance of the unit cell’s power and ground plane, \( R_{\text{Power,Ground}} \) which can be easily found in basic textbooks. As can be seen from Fig. 3(b), inductance and resistance of the ground plane must be added to those of the power plane in order to use the segmentation method. The segmentation method uses z-parameter matrices and in the z-parameter, impedance will be identical for the case when the inductance and resistance of the power and ground are separated and for the case when they are added together. Since inductance is calculated from air filled capacitance which considers power and ground plane together, inductance of the power and ground plane is already considered together in Eq. (12).

\[ L = \frac{1}{c^2} \times C_{\text{air}} \]  

\[ C_{\text{air}} = \epsilon_0 \frac{l_u^2}{t_{\text{total}}} \]  

\[ R = R_{\text{Power}} + R_{\text{Ground}}, \quad R_{\text{Power,Ground}} = \frac{1}{\sigma_m (l_u \delta_{\text{skin}})} \] 

\[ \delta_{\text{skin}} = \frac{1}{\sqrt{\pi f \mu \sigma_m}} \]  

As can be seen from Fig. 3(a), there exist probing pads for measurement to validate the proposed modeling method. The probing pads are modeled into two part: a single ground TGV and power/ground interconnection which is in form of transmission line. Inductance of the TGV which interconnects the ground probing pad in the M1 layer and the ground plane in the M3 layer can be derived from the magnetic energy in the unit cell defined by \( U_m = \frac{1}{2} \int \vec{B} \cdot \vec{H} \, dv \). Setting this equal to \( U_m = \frac{1}{2} I^2 L \) with periodic boundary conditions, we can derive the inductance of the TGV. Detailed derivation is given in [24]. The inductance of the tapered TGV (\( L_{\text{TGV}} \)) with length of \( t_{\text{total}} \) confined in the repetitive unit cell is written in Eq. (16). Resistance of the ground TGV can be found in chapter six of [25]. In this case, capacitance formed between ground TGV and power plane in M2 metal layer is ignored since the value will be so small which is associated with thickness of the metal layer and via clearance. Finally, the short transmission line structure which consists of micro-vias and measurement pads can be considered based on transmission line parameters summarized in chapter two of [26].

\[ L_{\text{TGV}} = \int_{z=0}^{t_{\text{total}}} \left[ \ln \left( \frac{d}{dS} \right) + \frac{dS}{l_u} - 1 \right] dz, \quad dS(z) = \pi \left( \frac{d_{\text{TGV}}}{2} + \frac{(d_{\text{TGV}} - d_{\text{TGV}})}{2t_{\text{total}}} z \right)^2 \]  

Proposed unit cell of the glass package PDN can now be fully expressed using the determined lumped parameters. By applying the segmentation method between adjacent unit cells, the whole
structure of the glass package PDN can be modeled and the impedance of the glass package PDN can be estimated. The proposed model can be used for any arbitrary shape of the PDNs. In this study, only one unit cell is considered which is rectangular PDN plus probing pads. However, it is possible to expand the modeling such as including via model, decoupling capacitors or other interconnection such as pads as long as these models can be expressed into z-parameter matrices. In previous study [27], it is shown that also other various types of PDN such as mesh or grid type PDN can be converted into plane type unit cell PDN. Therefore, it is important to verify the basic unit cell structure first and then expand the research toward more complex structures.

3. Verification of the proposed modeling method based on measurement and simulation

In this section, the proposed modeling method for glass package PDN impedance estimation is validated based on measurement and simulation. The designed glass package PDN is fabricated for experimental verification. Also, the design file is imported to 3D-EM solver, Ansys HFSS and then PDN impedances are extracted. Measured and extracted PDN impedances are compared to that of estimated results based on the proposed modeling method.

Figure 5 shows photographs of the fabricated glass package test coupons including various types of test vehicles. In the coupon shown in Fig. 5(a), test vehicles for the verification of the glass package PDN model are included. Measured impedances from these test vehicles are compared with the results derived using the proposed method and extracted results from 3D-EM simulation. In Fig. 5(b), test vehicles for the measurement of PDN resonance effects on the signal/power integrity are shown.

Using microprobe (picoprobe GSG, GSSG and GS type with 250 μm pitch, GGB industries Inc.), calibration kit (#CS-9 and #CS-14, GGB industries Inc.) and coaxial cables (W.L. Gore & Associates, Inc.), experimental verification has been conducted in both time and frequency domain. The frequency-domain measurements of glass package PDN impedance and channels are conducted up to 20 GHz using Vector Network Analyzer (VNA). The VNA, model N5230A from Agilent Technologies, has a bandwidth covering the frequency range from 300 kHz to 20 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 were used.

To verify the proposed modeling method, estimated impedance curves based on the proposed modeling method are compared with those of measurement and simulation up to 20 GHz. First, a test vehicle which is shown in Fig. 5(a) and described in Fig. 3(a) was measured with GS-type micro-probe. Impedance properties of the glass package PDN were measured at the edge and size probing pads. However, at the center of the glass package, due to failure developed during the fabrication processes, ground redistribution layer (RDL) on M2 layer was disconnected with the ground TGV. Due to this reason, impedance of the glass package PDN at the center could not be measured.

For the glass package PDN impedance simulation, designed test vehicle was simulated using 3D-EM solver HFSS from Ansys under the computational resources of Intel(R) Xeon CPU @ 2.53GHz and 48-GB RAM. For the glass package PDN impedance estimation based on the proposed modeling method, MATLAB was used for impedance property estimation under the computational resources of Intel(R) Core(TM) i5-4900 CPU @ 3.5GHz and 16-GB RAM.

The PDN impedance curves obtained from the proposed modeling method using MATLAB show good correlation with the measurement and simulation results in the frequency range from 0.1 GHz to 20 GHz, as shown in Figs. 6 and 7. Figure 6 is a comparison of the PDN impedance measured and simulated at the side-probing pad with proposed modeling based result, where as Fig. 7 is a comparison conducted at the edge-probing pad. As can be seen from the Figs. 6 and 7, impedance curves obtained based on the proposed modeling method align well with the measured and simulated impedance curves at the frequency range where capacitance and inductance of the PDN dominate the impedance properties. Also, by adopting the proposed method, less estimation time and computational resources are required, which are summarized and compared in Figs. 6 and 7. As frequency goes higher, standing waves are generated in the glass package PDN resulting in generation of mode resonances. Using the
parameters determined in the previous section, mode resonance frequencies, $f_{m,n}$ can be estimated using Eq. (17). At these frequencies, sharp impedance peaks can be generated depending on the location of the impedance-observing points. In the ideal PDN with rectangle shape, these locations can be calculated based on standing wave analysis. However, for actual PDN with various shapes, estimation of the locations affected by the mode resonance is almost impossible to be calculated by simple equation. Since the proposed modeling is based on the segmentation method, impedance estimation for arbitrary shapes can be easily conducted.

$$f_{m,n} = \frac{c}{2\pi \sqrt{\epsilon_{\text{mix,real}}} \sqrt{\left(\frac{m\pi}{l_x}\right)^2 + \left(\frac{n\pi}{l_y}\right)^2}}$$  \hspace{1cm} (17)

Frequency where the first series resonance is generated by the total capacitance and the inductance associated with physical parameters of the glass package PDN, measured impedance is little bit higher than that of proposed model based estimation. Also at the mode resonance frequencies, measured PDN impedances are lower than estimated impedance. These differences are caused by the contact resistance between the probing pads and the micro-probes. This contact resistance is added to the PDN impedance profile and as a result, additional resistance value is observed at the series resonance frequency. Impedance magnitudes at the mode resonance frequencies are dominated by the Q-factor. Due to the contact resistance, the Q-factor is affected which reduced the magnitude of the impedance peaks at the mode resonance frequencies. Except for these differences, proposed model estimated the impedance of the glass package PDN accurately.

As mentioned in the introduction of this manuscript, the glass substrate is one of the superior alternative package substrates to solve issues of current silicon packages. Recently, silicon packages and interposers are widely adopted, however, fabrication yield is limited as the package dimensions increase which is associated with limitation of 12-inch silicon wafer. Also, finite conductivity of the
Fig. 6. Estimated glass package PDN impedance at the side-probing pad is compared with measured and simulated results. Impedance estimated based on the proposed modeling method shows good correlation with measurement and simulation.

Fig. 7. Estimated glass package PDN impedance at the edge-probing pad is compared with measured and simulated results. Impedance estimated based on the proposed modeling method shows good correlation with measurement and simulation.

Silicon substrate causes signal integrity degradation at higher frequency range. The glass substrate is gaining attention because advantages of the glass substrate can cover limitations of the silicon substrate. Therefore, not only fabrication processes but also electrical design, test, and modeling methodologies are gaining attention in the glass packaging researches. In previous research [28], the glass package PDN resonance was first analyzed and verified with test vehicle fabrication and measurement. However, glass package PDN modeling and analysis were simplified into lumped RLC network or simulation. Therefore, the proposed method for the first time, estimated glass package PDN impedance properties accurately, especially at mode resonance frequencies and locations. Also, glass package test vehicles were fabricated and measured to support the proposed method. Compared to conventional partial element equivalent circuit (PEEC) method [29] which is based on complex Green's function analysis, the proposed method is based on relatively simple Z-parameter calculation.
which directly derives unit cell parameters from physical structure and dielectric modeling.

In the following section, analysis of glass package PDN resonances on signal and power integrity is summarized. Since proposed PDN modeling method can accurately estimate the appearance of the impedance peaks at the mode resonance frequencies and locations, proposed model can be useful for defining the locations vulnerable to the PDN resonances at the early design stage.

4. Measurement and analysis of glass package PDN resonance effects on a high-speed through glass via (TGV) channel

In this section, effects of the glass package PDN resonance on a high-speed through glass via (TGV) channel are measured and analyzed. First, insertion loss of glass package channel with and without TGV transitions are measured and compared. When TGV transitions are included, it has a chance that at certain frequencies, signal integrity of the channel is affected by the glass package PDN. Also the insertion loss of the glass package channel with TGV is compared with the PDN impedance measured near the signal TGV to analyze the PDN resonance effects.

Next, eye-diagram of channel with and without TGV transition is measured and compared at the resonance frequencies. Impact of high resonance peaks generated by the low loss of the glass package substrate on signal to PDN coupling is analyzed by far-end crosstalk (FEXT) and noise coupling measurements. Low loss of the glass substrate generated sharp PDN impedance peaks affecting the return current of the TGV channel. Due to the high impedance between power and ground planes at the mode resonance frequencies, return current is loaded in the PDN, causing various signal and power integrity issues.

To analyze the glass package PDN resonance effects on the signal and power integrity, two test vehicles were measured in the frequency and time-domain. Figures 8(a) and (b) show a top view of the measured test vehicles and a cross-sectional view of the via transition structure in the test vehicles is shown in Fig. 8(c). Test vehicle described in Fig. 8(a) is designed and fabricated to measure the insertion loss and eye-diagram of the glass package channels and PDN impedance near the signal TGV. There are two channels; one is designed on the top layer (M1) in the form of single-ended micro-strip line with line width of 50 $\mu$m and the length of 12 mm. The other is the single-ended micro-strip line with TGV transitions. Channel lengths on M1 and M4 layer described with $l_{M1}$ and $l_{M4}$ are 2 mm and 8 mm respectively. Channels on M1 and M4 are interconnected with TGVs and its cross-sectional view is depicted in Fig. 8(c). Insertion loss in the frequency-domain and eye-diagram were measured with GSG-type micro-probes. On M2 and M3, power and ground plane with 16mm and 14mm in the $x$ and $y$ directions were designed. 120 $\mu$m Away from the signal TGV, GSG probing pad to measure the PDN impedance are designed. Measurement results using the test vehicle shown in the Fig. 8(a) are summarized in Figs. 9 and 10.

Test vehicle described in Fig. 8(b) is designed and fabricated to measure the far-end cross-talk (FEXT) in the frequency and time domain. Measurement results using the test vehicle shown in the Fig. 11. On M2 and M3, power and ground plane with 16 mm and 16 mm in the $x$ and $y$ directions were designed. Two coupled channels are designed with and without TGV transitions to compare PDN resonance impact 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 $\mu$m. For the coupled channels with the TGV transitions, channel length on M1 and M4 layer described with $l_{M1}$ and $l_{M4}$ are set to be both 4 mm. In order to neglect unwanted reflection effects, these channels were measured with GSSG-type micro-probes to provide 50 ohm termination to the other probing pads except for the pad where the FEXT is measured.

In Fig. 9, measured insertion losses of the glass package channels and the PDN impedance are compared. The measured insertion losses of the glass package channel with and without TGV transitions are shown in Fig. 9(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. 9(b) which compares the measured insertion loss of the channel with TGV and the PDN impedance measured adjacent to the
Fig. 8. To analyze the glass package PDN resonance effects on signal/power integrity, two test vehicles were fabricated and measured. Top view of each test vehicle is depicted in (a) and (b). In the test vehicle shown in (a), single ended channels with and without TGV transitions exist. Insertion loss and eye-diagram were measured. Probing pad to measure the PDN impedance adjacent to the signal TGV is also located to compare insertion loss with PDN impedance. In the test vehicle shown in (b), coupled lines with and without TGV transitions are included to measure the far-end cross-talk. In (c), cross-sectional view of the channel with TGV transitions is shown.

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 for the resonance frequencies. At the resonance frequencies where high PDN impedance peaks are generated, return current of the channel is affected since high impedance PDN takes more power than the receiver. As a result, return current is loaded to the PDN causing vertical return current path discontinuity and the insertion loss is increased significantly for the channel with TGV transitions at the resonance frequencies. Also, loaded return current in the PDN can propagate along the PDN, causing PDN to channel coupling issues or edge radiation issues. At these frequencies, signal quality at the receiver side is expected to be degraded. Eye-diagrams were measured to verify the return current loading effects and signal integrity degradation in the channel caused by the glass package PDN resonance which is shown in Fig. 10.

Eye-diagrams of the glass package channel with and without TGV transitions are measured at 7,880 Mbps which corresponds to PDN’s (1, 0) mode resonance frequency. Figure 10(a) shows the eye-diagram of the package 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 the 1-unit interval) at 7,880 Mbps. Figure 10(b) shows the eye-diagram of package 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 the 1-unit interval) at 7,880 Mbps. When PDN impedance peak is generated close to the signal TGV at the resonance frequency, signal quality is degraded both in the frequency-domain and the time-domain as can be seen from Figs. 9 and 10.

Also far-end cross-talk (FEXT) between coupled channels located faraway is measured in the frequency-domain and the time-domain. Test vehicle shown in the Fig. 8(b) was measured. Measured results are plotted in Fig. 11.

The distance between coupled channels in the test vehicle measured is much larger than the channel.
Fig. 9. (a) Insertion loss of the glass package channels with and without TGV transitions are measured and compared. (b) Measured insertion loss of the channel with TGV transitions is compared with the PDN impedance measured adjacent to the signal TGV is compared. PDN mode numbers are also marked together.

width therefore it should less vulnerable to the FEXT issues. In Fig. 11(a), FEXTs in the frequency-domain are compared for the coupled package channel with and without TGV transitions. For the channel with TGV transitions, due to the high PDN impedance at the mode resonance frequencies which hold return current in the PDN, more cross-talk is coupled to the aggressor channel. When 3,970 MHz (7,940 Mbps 0/1 cyclic pattern) clock signal (0 to 1 V, 30 ps rising/falling time and all ports terminated with 50 ohm) which corresponds to the (1, 0) mode resonance frequency is injected to the coupled channel with TGV transitions, 53 mV (5.3% of the input voltage) FEXT was measured. This value is 10 times larger than the case when 5,000 MHz (10,000 Mbps 0/1 cyclic pattern) clock signal which corresponds to the non-mode resonance frequency is injected to the same coupled channel.

Impedance peaks associated with PDN resonance in the glass package cause significant signal and power integrity issues. When there are signal via transitions using TGVs, high impedance peaks generated by the PDN mode resonances disconnect return current path of the channel at certain
Fig. 10. Eye-diagrams of the glass package channel with and without TGV transitions are measured at 7,880 Mbps which corresponds to PDN’s (1, 0) mode resonance frequency. Test vehicle shown in Fig. 8(a) is used for experiment. (a) Without TGV transitions and (b) with TGV transitions.

frequencies. Therefore, return current is loaded in the PDN, increasing the channel loss, degrading eye-diagram and inducing PDN noise causing cross-talk to the channels even located faraway. There exist solutions such as shielding structures, decoupling capacitor schemes or even electromagnetic bandgap (EBG) structures to solve noise propagation along the PDN associated with mode resonances causing vertical return current discontinuity. But sometimes due to design rules and fabrication processes limitations, it might be difficult to design such structures. Therefore, it is important to estimate locations and frequencies where high PDN impedance peaks are generated to avoid placement of the signal TGVs. The proposed modeling method is powerful for the estimation of accurate impedance properties in the glass package PDN. Especially, the proposed method can accurately estimate locations in the PDN and frequencies where the signal TGV can be affected by the PDN mode resonances regardless of the PDN shape.

However, in this research, only basic structure including plane type PDN and probing pads are included. Currently, electrical design and modeling in the glass package is still at the basic research level with high potentials. Therefore, for the glass packages to be widely adopted in the near future, not only advancement in fabrication processes but also efficient modeling methodologies are needed.
In the future study, modeling of the glass package channels which are affected by the PDN will be added to the proposed model shown in this paper. Also, inclusion of different types of PDN unit cell such as voids in the PDN and decoupling capacitors remain as future tasks of this paper to reflect more complex and real package designs.

5. Conclusions
In this paper, an accurate glass package PDN model is proposed based on a segmentation method for the first time. The proposed method can be used for estimating the appearance of PDN impedance peaks associated with mode resonance depending on the locations and frequencies. The proposed modeling method for the glass package PDN impedance estimation is validated based on measure-
The designed glass package PDN is fabricated for experimental verification. Also, the design file is imported to the 3D-EM solver, Ansys HFSS and then PDN impedances are extracted. Measured and extracted PDN impedances are compared to that of estimated results based on the proposed modeling method. The PDN impedance curves obtained from the proposed modeling method using MATLAB showed good correlation with the measurement and simulation results in the frequency range from 0.1 GHz to 20 GHz.

Also, analysis of the glass package PDN resonance effects on the signal and power integrity were conducted based on measurement. Glass package PDN serves as a good return current path for signal TGVs. However, due to the low loss of glass substrate, sharp PDN impedance peaks are generated at the mode resonance frequencies. Due to these high impedance peaks, return current was discontinued and was kept at the PDN which resulted in the increase of insertion loss when there exist signal reference changes using TGVs. Measured eye-diagram of the channel with signal TGV transitions had smaller eye-opening voltage and larger timing jitter at the data-rate corresponds to the resonance frequency compared to those of the channel without signal TGVs. Lastly, PDN resonance effects on the FEXT in the frequency-domain and time-domain were measured and analyzed. For the loosely coupled channels located faraway from each other, more FEXT was induced at the input data rate corresponding to the frequency of the mode resonance. Therefore, it is important to estimate locations and frequencies where impedance peaks are generated in the glass package to fully take advantages associated with the glass package substrate. The proposed modeling method can be used for efficient estimation of not only PDN impedance but also vulnerable locations and frequencies for the high-speed channels in early design stage.

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