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Advanced materials for crosstalk and power optimization in TSV-enabled 3D ICs

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ABSTRACT

The continued scaling of semiconductor devices has exposed the limitations of traditional two-dimensional (2D) integrated circuit architectures. To address performance bottlenecks and interconnect constraints, the industry is increasingly adopting three-dimensional (3D) integration technologies. through-silicon vias (TSVs) are a fundamental enabler of this advancement, facilitating vertical signal transmission between stacked silicon layers. Despite their benefits, TSVs face critical challenges related to crosstalk, power dissipation, and signal delay issues that are especially pronounced in dense via arrays. This research explores the use of multi-walled carbon nanotube (MWCNT) based TSVs insulated with different dielectric liners, including silicon dioxide (SiO_2), PPC, polyimide, and benzocyclobutene (BCB). HSPICE simulations are used to evaluate crosstalk noise, power dissipation, power delay product (PDP), and energy delay product (EDP) across varying TSV pitches. Among the materials studied, BCB demonstrates the most promising results. Specifically, MWCNT TSVs with BCB at a 10,000 μm pitch achieve up to 58% reduction in functional crosstalk, 75% in dynamic crosstalk, 78% in power dissipation, and a 52% improvement in PDP compared to single-walled CNT (SWCNT) based TSVs. These findings confirm the suitability of combining MWCNT cores with low-k BCB liners for enhancing performance, energy efficiency, and signal reliability in advanced 3D integrated circuits.

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1. INTRODUCTION

Traditional two-dimensional (2D) integrated circuits (ICs) are becoming more difficult as the semiconductor industry moves toward ultra-large-scale integration (ULSI). Due to parasitic effects and routing constraints, Moore's Law's unrelenting transistor growth has hampered interconnect performance, power efficiency, and signal integrity [1], [2]. Three-dimensional integrated circuits (3D ICs) vertically integrate many silicon layers to minimise connection length, latency, bandwidth, and energy efficiency [3], [4]. ThreeD ICs depend on the through-silicon via (TSV), which allows direct vertical electrical connections between stacked dies. TSVs have a conductive core, dielectric insulating lining, and silicon substrate [5]. Copper is the traditional TSV core material because to its electrical and thermal conductivity, but electromigration, temperature-induced extrusion, signal loss from the skin effect, and mechanical breakdown under stress are important reliability difficulties [6], [7]. Carbon-based nanomaterials like single-walled CNTs (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) are being investigated as copper alternatives to address these constraints [8]-[10]. The cross-sectional structure of a SWCNT array placed in a dielectric layer over a silicon substrate is shown in Figure 1. A comparable setup utilising a MWCNT array as shown in Figure 2 shows nanotube architectural changes. These materials have good electrical, thermal, and mechanical qualities that improve TSV reliability and performance [11], [12]. The dielectric liner around the TSV reduces capacitive coupling and crosstalk, which are especially troublesome in closely packed TSV arrays [13], [14]. Low-k polymer-based dielectric materials including polyimide, polypropylene carbonate (PPC), and benzocyclobutene (BCB) are replacing conventional silicon dioxide (SiO_2) owing to their ability to reduce parasitic capacitance and enhance signal integrity [15]. MWCNT-based TSVs with different dielectric liners are compared to SWCNT-based TSVs in this work. Crosstalk noise, power dissipation, and power delay product (PDP) are examined over TSV pitch sizes. HSPICE-based simulations show that MWCNT TSVs insulated with BCB outperform SWCNT structures in all performance parameters, particularly at greater pitch values. The dielectric materials' permitivity and characteristics are shown in Table 1. Figures 1 and 2 show SWCNT and MWCNT arrays in dielectric-lined TSVs, highlighting their electrical and mechanical differences. A single graphene cylinder makes SWCNTs ideal for high-frequency, low-power applications owing to their strong electron mobility and homogeneous shape. MWCNTs boost current-carrying capacity and structural durability but increase inter-shell scattering and reduce mobility [16].

Table 1 evaluates the physical, thermal, electrical, and mechanical properties of four dielectric materials: SiO_2, Polyimide, PPC, and BCB. BCB has the lowest dielectric constant (2.65), making it appropriate for high-frequency or low-capacitance applications. Its low density and gentle thermal properties make it excellent for improved microelectronics packaging. Five primary parts make up the paper. Section 1 explains why the study is important in 3D IC technology. Section 2 reviews prior work and challenges in the literature. Section 3 describes the MWCNT-based TSV construction and electrical circuit in comparison. Simulation results and performance comparisons are in section 4. Section 5 reviews and offers additional research.

Table 1. The relative permittivities of the dielectric materials and their properties

S. No	Property	SiO_2	Polyimide	PPC	BCB
1	Relative Permeability (μr)	1	1	1	1
2	Relative Permittivity (εr) / Dielectric Constant (k)	3.9	3.5	2.9	2.65
3	Density (ρ)	2200 kg/m³	~1420 kg/m³	~1180 kg/m³	~1050 kg/m³
4	Thermal Conductivity (k)	1.4 W/mK	~0.12–0.35 W/mK	~0.2 W/mK	~0.29 W/mK
5	Specific Heat Capacity (Cp)	703 J/(kg·K)	~1090 J/(kg·K)	~1500 J/(kg·K)	~1250 J/(kg·K)
6	Electrical Conductivity (σ)	10^{-14} to 10^{-16} S/m	~10^{-15} S/m	~10^{-14} S/m	~10^{-15} S/m
7	Young's Modulus	70 GPa	~2.5 GPa	~1.3 GPa	~2.9 GPa
8	Poisson's Ratio	0.17	0.34	~0.36	0.34
9	Coefficient of Thermal Expansion (CTE)	0.5 ppm/°C	~20–55 ppm/°C	~60 ppm/°C	~42 ppm/°C

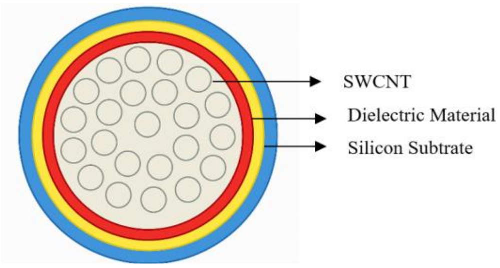

Figure 1. Cross-sectional view of SWCNT array with dielectric material and silicon substrate

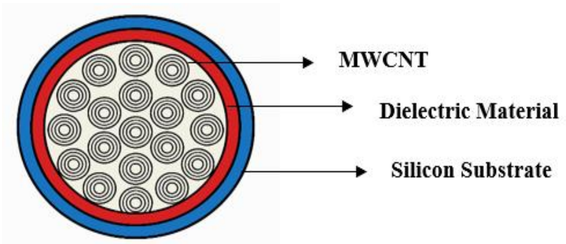

Figure 2. Cross-sectional view of MWCNT array with dielectric material and silicon substrate

2. LITERATURE SURVEY

Crosstalk, Signal distortion, delay fluctuations, and power inefficiencies result from capacitive and inductive coupling between nearby TSVs. A flurry of research on material-level and structural optimisations to reduce these undesirable interactions has followed. Carbon-based nanomaterials, especially MWCNTs, and low-k dielectric polymers that replace SiO_2 liners appear promising. Rajkumar and Reddy [11] presented heterogeneous coaxial TSVs with Cu-MWCNT composite cores and polymer liners, which reduced crosstalk owing to electrical isolation and impedance matching. Chen *et al.* [12] confirmed that connecting copper with MWCNTs in high-speed TSV designs can balance conductivity, reliability, and signal integrity. Experimentally, found that MWCNT-based TSVs with polymer liners reduce capacitive coupling and improve liner conformance, suppressing crosstalk. Kumari *et al.* [13] examined polymer liners in CNT-based TSVs, emphasising electrical and mechanical robustness throughout temperature cycles [14]. Kumar *et al.* [14] developed an FDTD-based modelling framework for MWCNT interconnects that captures complex electromagnetic behaviours and predicts crosstalk effects under different geometries. This helps validate design decisions before actual prototyping.TSV innovations now have a wider application base. Sreelatha *et al.* [15] investigated MWCNT TSVs in quaternary logic systems, a new logic design frontier. Their research showed that MWCNT bundles may greatly minimise signal coupling in multi-level logic circuits, expanding their use beyond binary systems. Pal *et al.* [16] introduced silicon-core coaxial TSVs, which, albeit not carbon-based, confirmed the relevance of coaxial symmetry in attenuating crosstalk in tightly packed TSV networks. Majumder *et al.* [17] examined mixed CNT bundles and found that heterogeneous SWCNT and MWCNT integration further reduces crosstalk latency and interconnect noise. Ramanathula and Anuradha [18] simulated CNT-based TSVs and found reduced crosstalk noise and power dissipation. Their findings demonstrate carbon nanoparticles' energy efficiency and high-frequency signal integrity. Sahu *et al.* [19] addressed metallic TSV eddy current effects, a neglected topic. Their comparison investigation showed that CNT bundles lower these currents, crosstalk, and power losses, making them better for GHz-range applications [20]. Carbon nanotechnology and modern polymer science are changing 3D IC TSV electrical and mechanical properties. Experiments and modelling show that MWCNT-based TSVs with low-k polymer liners may minimise crosstalk, improve signal integrity, and lower power consumption in next-generation VLSI systems. These advancements will help create robust, noise-resilient 3D IC designs as logic complexity increases and frequency domains grow [21]-[25].

3. PROPOSED COUPLED TSVS AND ITS ELECTRICAL EQUIVALENT MODEL

This section presents the structure of coupled MWCNT TSVs along with their circuit model shown in Figure 3. Moreover, the numerical expressions for MWCNT are also discussed.

$$R \;=\; R_{QT}\left(N_M \;\; \sum_{i=1}^{i=p} \mathrm{N}\, N_{iT}\lambda_{iT}\right).^{-1} \tag{1}$$

The resistance R for the proposed coupled TSVs is defined by Equation 1. In this design, R arises due to scattering effects such as TSV edge roughness, acoustic phonons, and static impurities. Here, R_{QT} indicates the quantum resistance, N_M signifies the total number of conducting channels, N_{iT} represents the number of conducting channels in the i-th shell, and λ_{iT} is the mean free path of electrons within that shell.

$$L = L_{MT} + L_{KT}(N_{TC})^{-1} \tag{2}$$

$$L_{MT} = \frac{\mu_0 \varepsilon_0}{C} \tag{3}$$

$$L_{KT} = \frac{h_{pc}}{4e^2 N_{TC} V_{fer}} \tag{4}$$

The inductance L arises from the combined effects of kinetic energy (L_{KT}) and magnetic energy (L_{MT}), both associated with the motion of electrons in distinct conducting channels are shown in equations 2, 3, and 4. This inductance is determined by assessing the energy contributions from these dynamic interactions. Important parameters involved in this assessment include the Fermi velocity (V_{fer}), TSV conducting Channel(N_{TC}), Planck's constant (h_{pc}), free space permeability, permittivity of vacuum, electron charge (*e*). The oxide capacitance is generated between the via and the silicon substrate, which is represented by the C_{oxide}. The Coxide can be calculated in equation 5. In the electrical equivalent model, C_Q and C_X are the quantum capacitance and parallel plate capacitance, and these can be stated in (6) and (7).

$$Coxide = 6.28 \frac{\varepsilon_r \varepsilon_0}{\left(\left(\frac{\frac{1}{2}D_M + D_G}{\frac{1}{2}D_M}\right)\right)} \tag{5}$$

$$C_Q = 4N_{TC}e^2/h_{pc}V_{fer} \tag{6}$$

$$C_X = \frac{2\pi\varepsilon R}{\frac{D_G}{D_M}} \tag{7}$$

the relative permittivity of the insulating material, permittivity of vacuum, and the distance between the via (D_M) bundle and the ground plane (D_G). The silicon substrate conductance can be represented G_{Sub} and these can be expressed in the (8) as:

$$G_{Sub} = \frac{\sigma_T \pi}{log\left(\sqrt{\left(\frac{D_{PT}}{2R_{TV}}\right)^2 - 1 + \frac{D_{PT}}{2R_{TV}}}\right)} \quad (8)$$

where $Dp_T$is the pitch between the two Vias, $\sigma_T = 0.1(\Omega.cm)^{-1}$ is the conductivity of substrate, R_{TV} is via radius.

Figure 3 shows a coupling analysis between two nearby TSVs in a 3D integrated system. The left RLC line represents the aggressor TSV, which switches and causes electromagnetic interference during signal transitions. Capacitive and inductive coupling may link this interference onto the neighbouring victim TSV (right RLC line), which is quiescent but vulnerable to noise. Cx and CQ simulate inter-TSV coupling, whereas R, L and substrate elements (Csub, Gsub) represent physical parasitics.

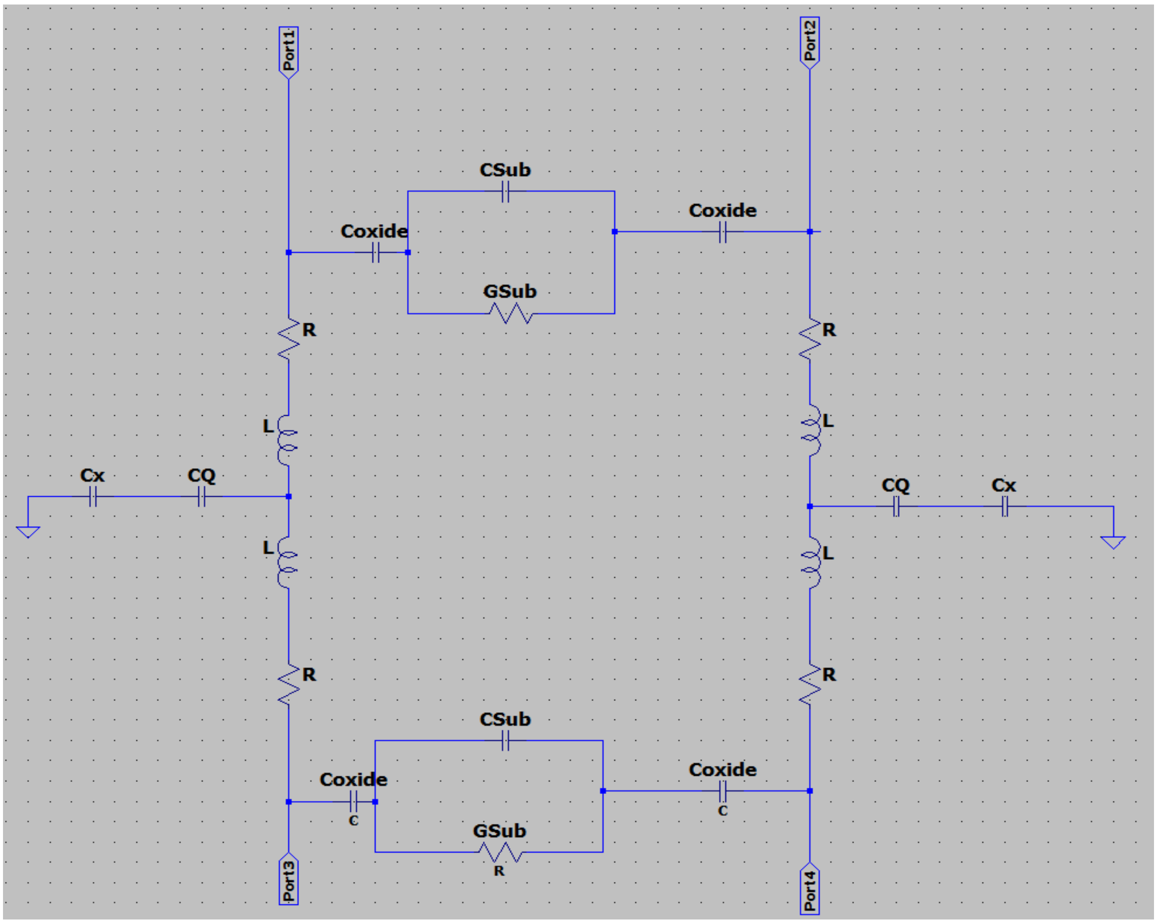

Figure 3. Electrical equivalent model of MWCNT-based TSVs

4. SIMULATION RESULTS AND DISCUSSIONS

The breakthrough MWCNT-based TSVs are hindered by crosstalk-induced noise, power dissipation, propagation delay product, and energy-delay product. Compare these performance metrics with various TSV pitch diameters and insulating lining materials. The expected MWCNT-based TSVs are compared to SWCNT ones. Functional and dynamic crosstalks are seen in TSVs switching. As an aggressive TSV changes, an idle victim TSV encounters functional crosstalk and voltage spikes. Dynamic crosstalk occurs when aggressor and victim TSVs switch concurrently. It has in-phase and out-of-phase delays. In-phase delays occur when both TSVs flip in the same direction, whereas out-of-phase delays occur when they switch directions simultaneously. MWCNT-based coupled TSVs' functional crosstalk, dynamic crosstalk, power consumption, propagation delay product, and energy-delay product were simulated using HSPICE. Functional crosstalk spikes a quiescent (victim) TSV when an aggressor TSV changes. Our research shows that crosstalk noise reduces with TSV pitch from 50 to 10,000 µm. SWCNT and MWCNT TSVs crosstalk noise was examined across dielectric materials.

Figure 4 indicates that all dielectric materials reduce crosstalk noise as TSV pitch increases, implying less electromagnetic interference with space. BCB has the lowest crosstalk among TSV pitches, proving its insulation. SiO_2 has considerable noise, whereas Polyimide and PPC perform fairly, with PPC slightly outperforming Polyimide at higher pitches. The best signal interference suppressor, BCB reduces noise as pitchwidens. This suggests that BCB and higher TSV pitch may enhance interconnect signal integrity. As TSV pitch rises, all dielectric materials reduce crosstalk noise as shown in Figure 5. BCB has the lowest crosstalk, particularly at higher pitches, reducing MWCNT signal interference. SiO_2 has the most crosstalk across all pitch levels, indicating inferior isolation. PPC reduces noise more than Polyimide at wider pitches. This shows that TSV pitch and dielectric material choice optimise MWCNT-based connection signal integrity. SWCNT devices with BCB dielectric exhibit far higher crosstalk noise than MWCNT structures at all TSV pitch levels as shown in Figure 6. MWCNT noise reduction rises from 55% to 58% with pitch, enhancing signal integrity. Higher pitches lessen capacitive coupling, improving performance. Noise difference shows SWCNTs reduce interference. Crosstalk is minimised more by MWCNT with BCB than ordinary interconnects. Active coupling causes dynamic crosstalk when aggressor and victim TSVs transition simultaneously creating signal interference. Functional crosstalk—when just the aggressor changes and the victim stays the same—interferes more. Dynamic crosstalk has real-time concurrent transitions, whereas functional crosstalk interferes under controlled switching.

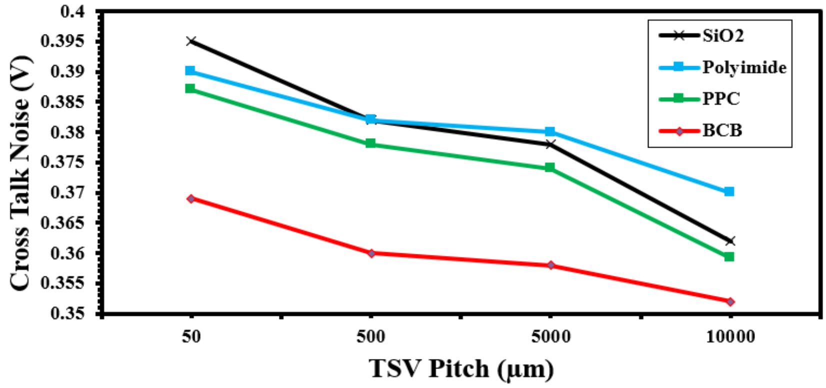

Figure 4. TSV pitch impacts functional crosstalk noise in SWCNT interconnects with different dielectric materials

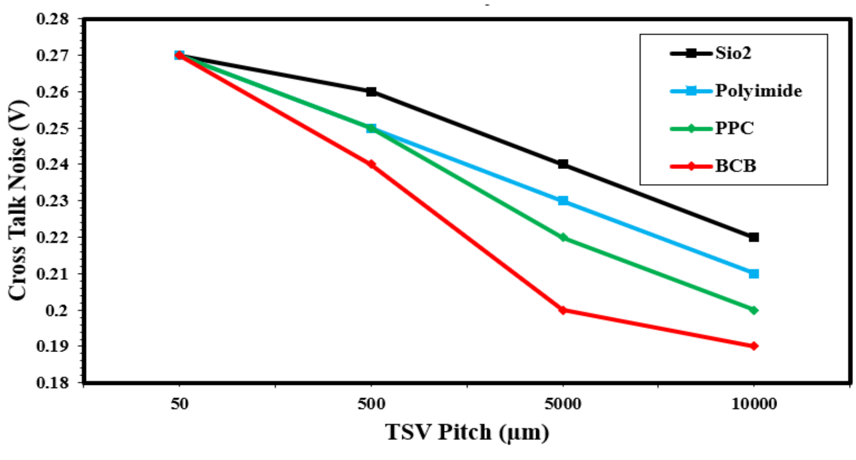

Figure 5. Impact of TSV pitch on crosstalk in MWCNT interconnects

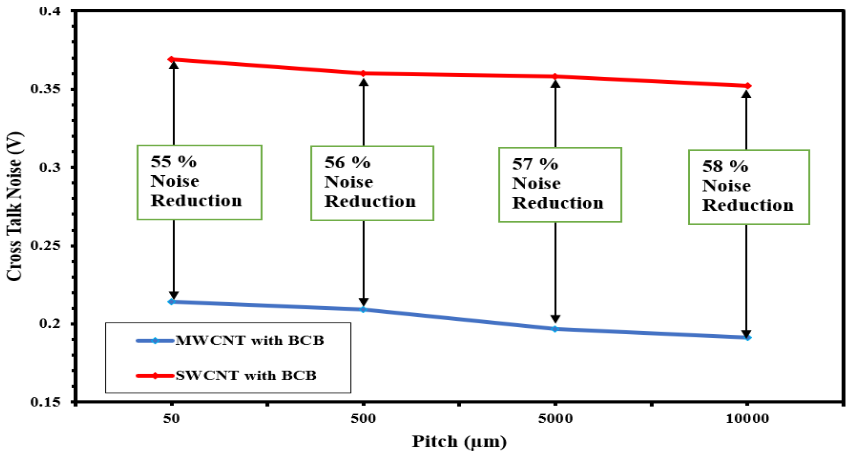

Figure 6. SWCNT and MWCNT functional crosstalk noise reduction comparison interconnects with BCB dielectric at different TSV pitches

Figure 7 shows dynamic crosstalk noise in SWCNT-based TSV structures with different pitches and dielectrics. Increasing TSV pitch reduces crosstalk in all dielectrics. BCB offers the strongest dynamic noise reduction, followed by PPC, Polyimide, and SiO_2. The graphic shows BCB's simultaneous switching dielectric performance enhancement. Figure 8 shows MWCNT-based TSVs' dynamic crosstalk noise for different dielectric materials. BCB has the lowest crosstalk noise across all TSV pitches. Very good noise coupling shielding. The best BCB noise reduction occurs as TSV pitch rises. BCB decreases 3D IC dynamic crosstalk best. SWCNT and MWCNT TSVs with BCB dielectrics are tested for dynamic crosstalk noise in Figure 9. MWCNT has far lower noise than SWCNT at all TSV pitches. Noise reduction rises with pitch from 72% to 75%. This suggests MWCNT with BCB isolates noise better than SWCNT. MWCNT with BCB reduces dynamic crosstalk in 3D ICs. Figure 10 demonstrates SWCNT-based TSV power dissipation trends for different dielectric materials as TSV pitch increases. Every pitch, BCB releases the least power. SiO_2 exhibits the highest power loss, leading in worse energy efficiency. BCB decreases nanoscale connection power consumption, researchers found. BCB is the most energy-efficient SWCNT dielectric.

Figure 11 demonstrates MWCNT-based TSV power dissipation with different dielectrics. BCB uses the least power at all TSV pitches. In contrast, SiO_2 dissipates the most electricity. All materials use less power as TSV pitch increases, but BCB is most efficient. BCB MWCNT connecting dielectric is most power-efficient. BCB dielectric SWCNT and MWCNT TSV power dissipation is seen in Figure 12. MWCNT saves electricity at all TSV pitches. Noise is reduced by 75%–78% with pitch. These results illustrate MWCNT's energy efficiency advantage over SWCNT. Thus, MWCNT with BCB lowers 3D IC power loss and noise.

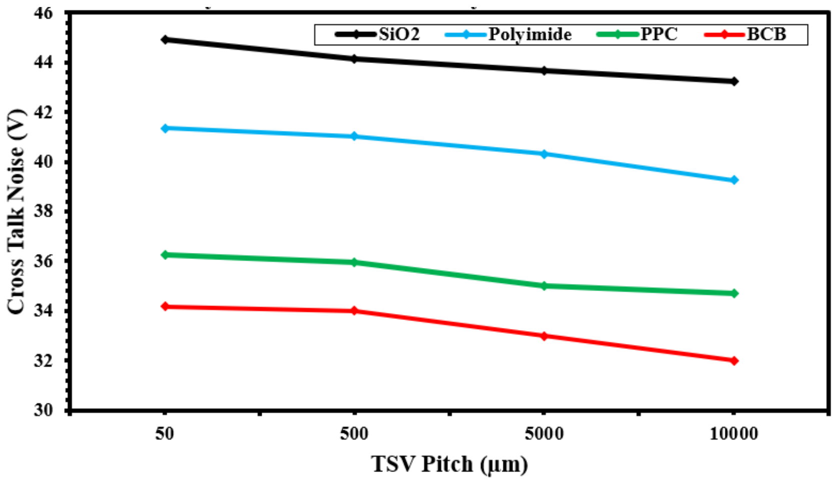

Figure 7. Evaluation of dynamic crosstalk noise in SWCNT-based TSVs with various dielectric materials

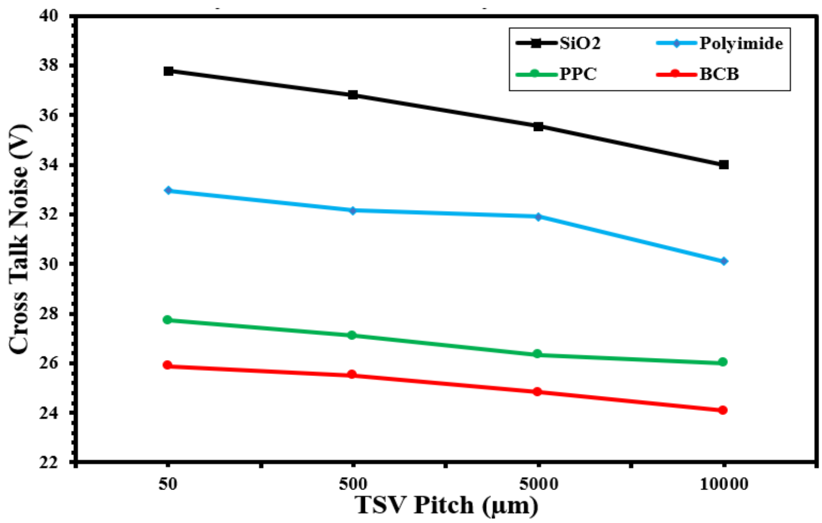

Figure 8. Evaluation of dynamic crosstalk noise in MWCNT-based TSVs with various dielectric materials

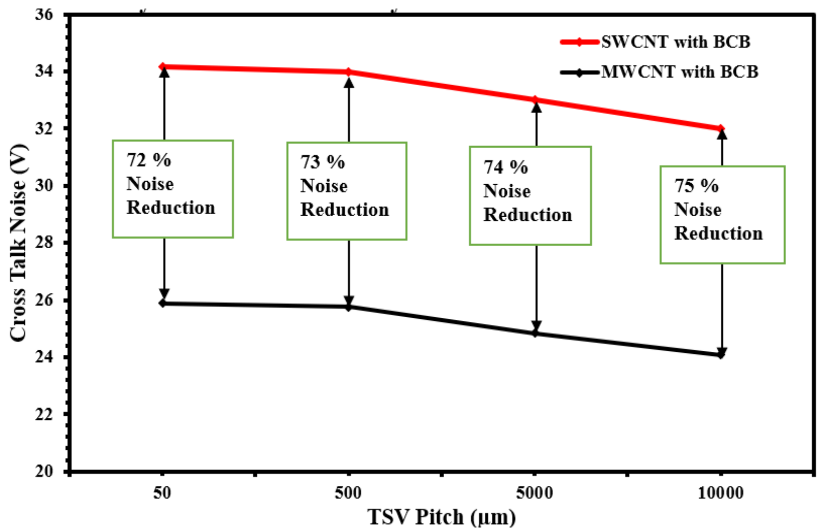

Figure 9. Comparative analysis of crosstalk noise in SWCNT and MWCNT with BCB dielectric

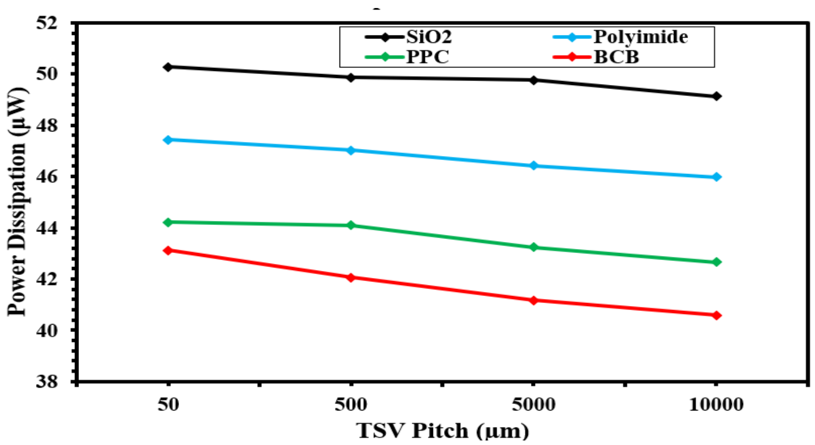

Figure 10. Evaluation of power loss in SWCNT-based TSVs using various dielectrics

This research evaluates CNT-based TSV with PDP. With delay and dynamic crosstalk noise, PDP mimics power loss and signal interruption. Use femtojoules to double power loss and crosstalk noise. SWCNT and MWCNT PDP were compared. MWCNT regularly lowers PDP, increasing energy efficiency and signal degradation. SWCNT-based TSV PDP depend on TSV pitch in Figure 13. BCB has the lowest PDP, suggesting superior power dissipation and dynamic crosstalk noise. SiO_2 has the greatest PDP, indicating inefficiency. Reduced coupling lowers PDP in all materials as TSV pitch rises. Dielectric choice significantly affects TSV connection energy efficiency, according to trends.

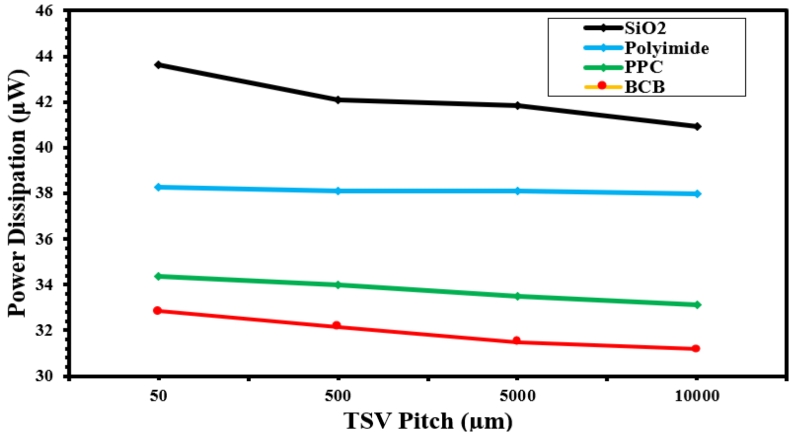

Figure 11. Analysis of power dissipation in MWCNT TSVs with various dielectric insulators

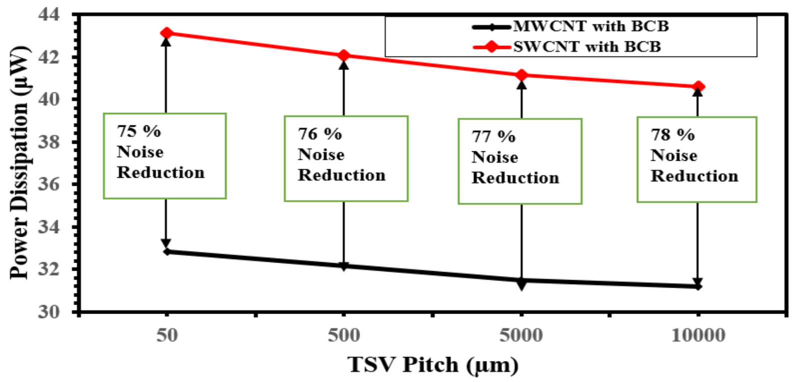

Figure 12. Comparative study of power efficiency in SWCNT and MWCNT TSVs using BCB insulation

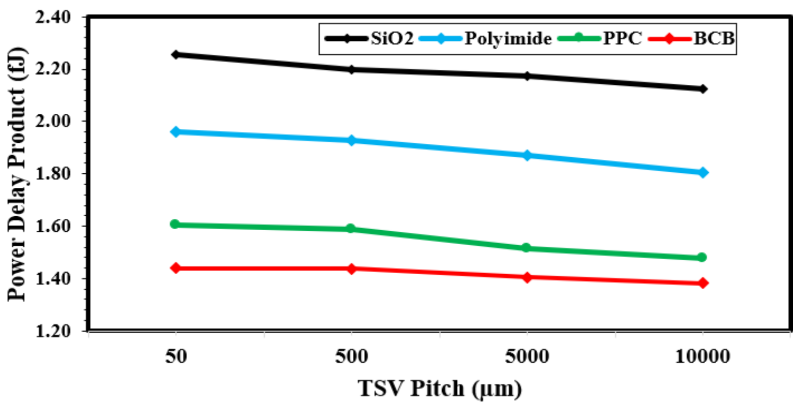

Figure 13. Power-delay product evaluation in SWCNT-based TSVs using different dielectrics

Figure 14 demonstrates MWCNT-based TSV PDP trends with various dielectric insulators. BCB has the lowest PDP, suggesting good signal and energy. SiO_2 might have the largest PDP, indicating more energy loss. Increased TSV pitch decreases capacitive coupling and PDP in all materials. BCB increases 3D IC connection efficiency, stats show.BCB-based SWCNT and MWCNT interconnects with varying TSV pitches for PDP are shown in Figure 15. MWCNT interconnects have lower PDP than SWCNT at all pitches. Overall, MWCNT constructions conserve energy. PDP drops 52%–58% with TSV pitch. This significant rise shows MWCNTs enhance signal transmission. Lower MWCNT PDP reduces power loss and signal latency. PDP decreases with pitch, improving this advantage. Superior dielectric characteristics of BCB insulation boost efficiency. Power-conscious 3D ICs benefit from MWCNTs' performance. BCB and MWCNTs may minimise dense connection latency and energy.

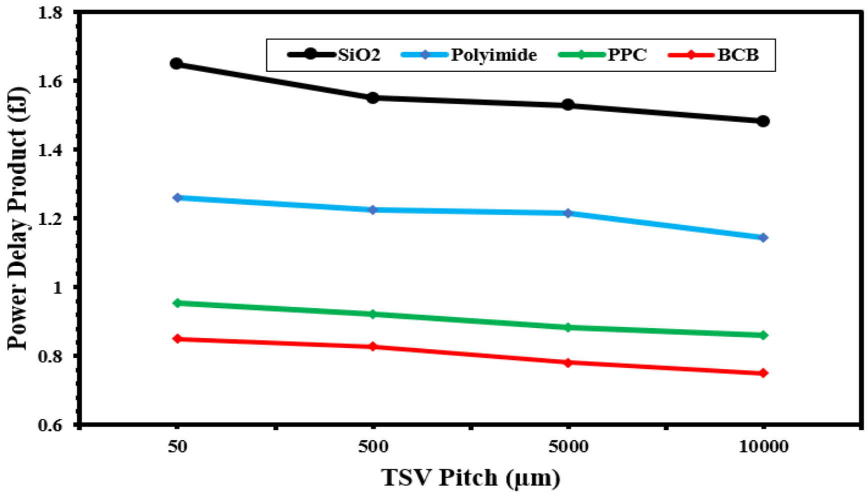

Figure 14. Power-delay product evaluation in MWCNT-based TSVs using different dielectrics

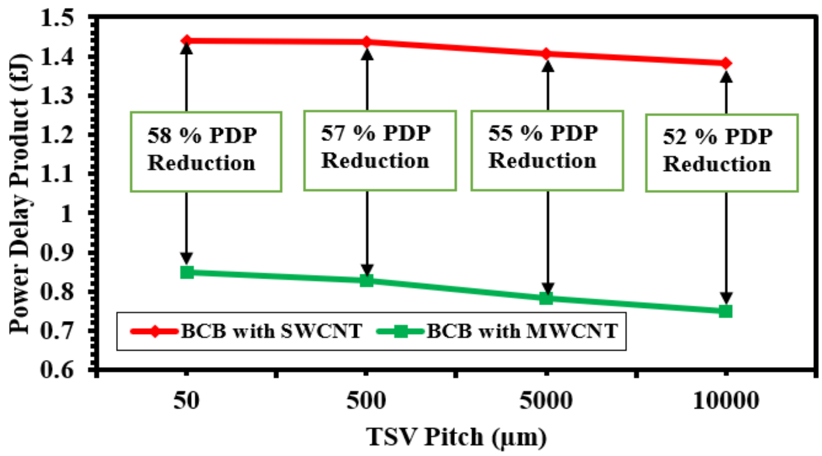

Figure 15. Comparative energy efficiency analysis of BCB-based SWCNT and MWCNT TSVs using PDP

5. CONCLUSION

In this work, crosstalk, delay, power consumption, and PDP were analyzed for MWCNT-based TSVs incorporating SiO_2, PPC, Polyimide, and BCB dielectric materials. The proposed TSV structures were modeled and evaluated using the HSPICE simulation tool. Among the evaluated materials, BCB-lined TSVs exhibited the best performance enhancements. A comparative analysis was also conducted against SWCNT-based TSVs using BCB at different TSV pitches (50 µm, 500 µm, 5000 µm, and 10000 µm). Simulation outcomes revealed that the proposed MWCNT TSVs achieved reductions of up to 58% in functional crosstalk, 75% in dynamic crosstalk, 78% in power dissipation, and 52% in PDP. These findings confirm that MWCNTs integrated with BCB liners can significantly enhance the performance of 3D integrated circuits.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Tappeta Chinna Sanjeeva Rayudu	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓			
Merrin Prasanna Nagadasari						✓			✓			✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

ETHICAL APPROVAL

No human participants or animals were involved in this research. Therefore, ethical approval and informed consent were not required.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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