engineering proceedings

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Proceeding Paper

Empowering Smart Surfaces: Optimizing Dielectric Inks for In-Mold Electronics †

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† Presented at the 1st International Conference on AI Sensors & the 10th International Symposium on Sensor Science, Singapore, 1–4 August 2024.

Abstract: Dielectric materials have gained traction for their energy-storage capacitive and electrically insulating properties as sensors and in smart surface technologies such as in In-Mold Electronics (IME). IME is a disruptive technology that involves environmentally protected electronics in plastic thermoformed and molded structures. The use of IME in a human–machine interface (HMI) provides a favorable experience to the users and helps reduce production costs due to a smaller list of parts and lower material costs. A few functional components that are compatible with one another are crucial to the final product's properties in the IME structure. Of these components, the dielectric layers are an important component in the smart surface industry, providing insulation for the prevention of leakage currents in multilayered printed structures and capacitance sensing on the surface of specially designed shapes in IME. Advanced dielectric materials are non-conductive materials that impend and polarize electron movements within the material, store electrical energy, and reduce the flow of electric current with exceptional thermal stability. The selection of a suitable dielectric ink is an integral stage in the planning of the IME smart touch surface. The ink medium, solvent, and surface tension determine the printability, adhesion, print quality, and the respective reaction with the bottom and top conductive traces. The sequence in which the components are deposited and the heating processes in subsequent thermoforming and injection molding are other critical factors. In this study, various commercially available dielectric layers were each printed in two to four consecutive layers with a mesh thickness of 50–60 µm or 110–120 µm, acting as an insulator between conductive silver traces overlaid onto a polycarbonate substrate. Elemental mapping and optical analysis on the cross-section were conducted to determine the compatibility and the adhesion of the dielectric layers on the conductive traces and polycarbonate substrate. The final selection was based on the functionality, reliability, repeatability, time-stability, thickness, total processing time, appearance, and cross-sectional analysis results. The chosen candidate was then placed through the final product design, circuitry design, and plastic thermoforming process. In summary, this study will provide a general guideline to optimize the selection of dielectric inks for in-mold electronics applications.

Keywords: in-mold electronics; dielectric ink; smart surface industry

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Citation: Hong, P.; Chin Yuan, G.S.; Tan, Y.M.; Wan, K. Empowering Smart Surfaces: Optimizing Dielectric Inks for In-Mold Electronics. *Eng. Proc.* **2024**, *78*, 8. https://doi.org/10.3390/engproc2024078008

Academic Editor: Po-Liang Liu

Published: 6 February 2025

1. Introduction

IME is a disruptive, electronics additive manufacturing technology integrating printed decorations and multi-functional electronics printed with conductive and dielectric inks [1] into a plastic structure. Compared to other electronics additive manufacturing types, its advantages are a high production rate, simplified manufacturing, and that it does not involve laser or chemical plating processes. IME provides a low-cost, high-efficiency, and customizable solution to the electronics industry, and hence has gained traction in human–machine interface (HMI) applications for its user experience, aesthetic design, simplification, miniaturization, lightweight, reduced material, and reduced maintenance costs and waste.

Commercial thermoformable electronic pastes and dielectric inks were printed in layers onto substrates [2] and underwent curing before being thermoformed [3] into three-dimensional shapes (Figure 1). These were then placed in an injection mold where resin was injected behind (Figure 2). To meet requirements, a reliable, compatible, commercial dielectric ink that is tolerant to heating processes is paramount to the success of the smart surfaces in HMI.

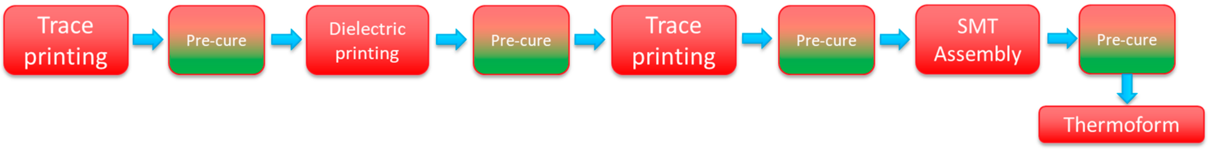


Figure 1. Process flow for printing conductive layers and dielectric layers through thermoforming in IME technology.

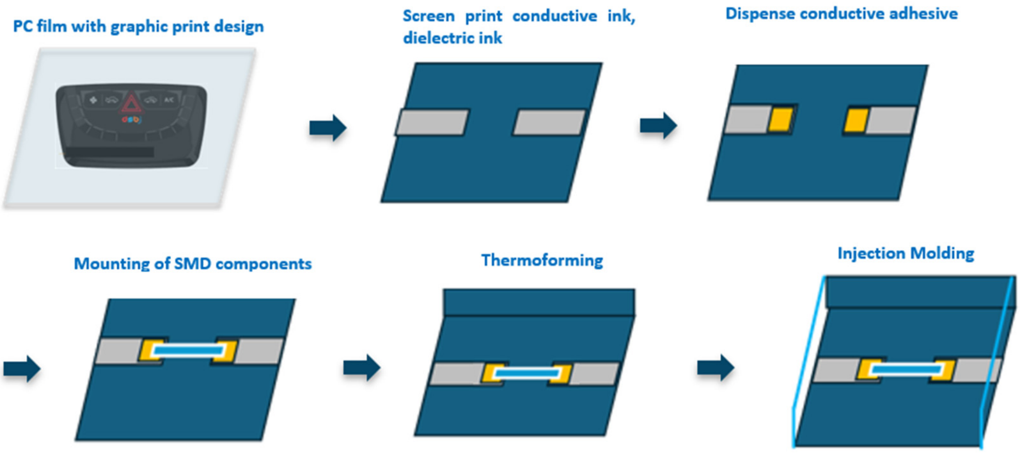


Figure 2. Manufacturing process flow for in-mold electronics (IME).

Dielectric inks provide insulation for preventing current leakage in multilayered printed structures and capacitance sensing on the smart surfaces of specially designed products. To meet these requirements, a reliable, compatible, commercial dielectric ink that is tolerant to heating processes [4] is paramount to the success of the smart surfaces in HMI to achieve a smart, touch-sensitive surface.

The aim of this study is to provide a preliminary assessment of commercially available dielectric inks that are suitable for use in the in-mold electronics industry [5] to establish (a) the selection of a suitable dielectric ink and (b) a guideline for dielectric ink selection considerations and (c) provide a glimpse of know-how in formulating and tweaking dielectric ink properties for IME applications.

2. Methodology

Screen-printing of dielectric traces is the transferring of the inks by passing through the patterned stencil with a squeegee. These inks are printed onto polycarbonate substrates (Figure 3a).

Numerous parameter testing was essential for optimized printing with optimal conditions (Table 1). The thicknesses of the different dielectric ink types is significantly and collectively affected by the mesh size and tension, the squeegee pressure and speed, and the curing process.

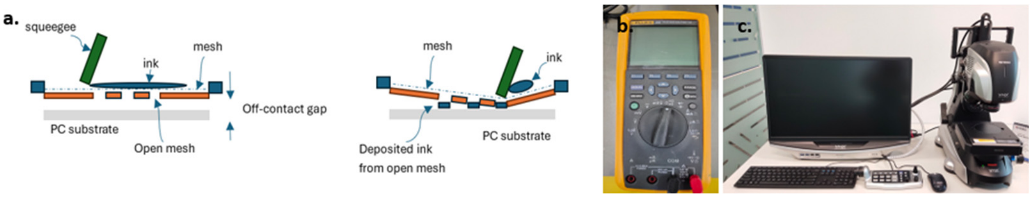


Figure 3. (**a**) Screen-printing by transfer of ink through open mesh to the substrate with a squeegee; (**b**) multimeter; (**c**) Keyence VHX-7000 Microscope.

Table 1. Optimized screen-printing parameters adopted in this study (equipment: Micro-tec screen printer, Singapore).

Mesh Parameters		Printing Parameters	
Mesh Size	**Mesh Thickness**	**Pressure**	**Speed**
Mesh count	µm	MPa	mm/s
250	50–60, 110–120	0.1–0.5	20–40

After curing, printed parts were subjected to resistance measurements using a Fluke 289 multimeter (Figure 3b). The dielectric trace width was measured using a Keyence VHX-7000 microscope (Figure 3c) and its thickness was measured by cross-section and SEM.

The printed parts were then subjected to thermoforming and injection molding processes that involved high heat, vacuum forming, elongation, and high shear stress. Thermoforming (Figure 4a–e) is the process that creates 3D shapes from flat 2D functional films with printed circuitry and mounted components via high-temperature vacuum forming. Injection molding is a process that involves placing thermoformed objects into an injection mold and inject heated molten polymer with pressure from behind.

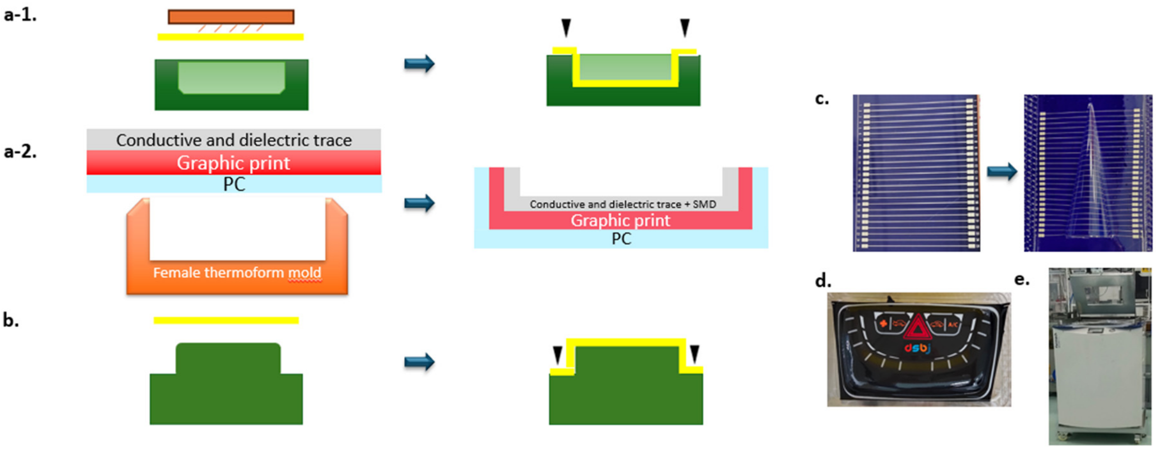
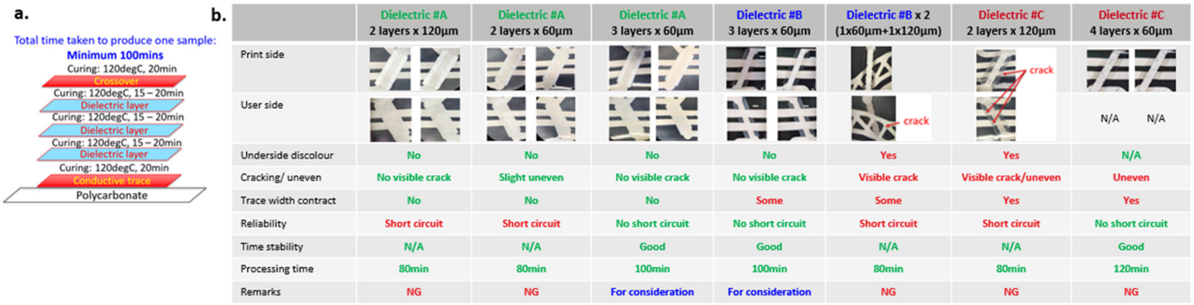


Figure 4. (**a-1**) Thermoforming in a female mold; (**a-2**) Thermoforming of printed circuitry in a female mold; (**b**) thermoforming in a male mold; (**c**) printing on flat polycarbonate substrate and thermoformed into cone-shape; (**d**) graphics with thermoforming; (**e**) thermoform equipment Formech, Singapore.

3. Results and Discussion

Dielectric ink types with different thicknesses were printed at 50–60 µm and 110–120 µm and cured. They were then subjected to quality and functionality checks for the presence of cracks, conductive–dielectric interface conditions, cross-sectional appearance, reliability, repeatability, and time stability (Figure 5). To facilitate the selection, the criteria were based on the (I-a) number of layers × deposition quantity/layer, (I-b) processing time,

(II) printing quality and cross-sectional analysis, (III) reliability and presence of short circuits, (IV) repeatability, and (V) time stability at six months.



	Dielectric #A 2 layers x 120µm	Dielectric #A 2 layers x 60µm	Dielectric #A 3 layers x 60µm	Dielectric #B 3 layers x 60µm	Dielectric #B x 2 (1x60µm+1x120µm)	Dielectric #C 2 layers x 120µm	Dielectric #C 4 layers x 60µm
Print side						crack	
User side					crack		N/A N/A
Underside discolour	No	No	No	No	Yes	Yes	N/A
Cracking/ uneven	No visible crack	Slight uneven	No visible crack	No visible crack	Visible crack	Visible crack/uneven	Uneven
Trace width contract	No	No	No	Some	Some	Yes	Yes
Reliability	Short circuit	Short circuit	No short circuit	No short circuit	Short circuit	Short circuit	No short circuit
Time stability	N/A	N/A	Good	Good	N/A	N/A	Good
Processing time	80min	80min	100min	100min	80min	80min	120min
Remarks	NG	NG	For consideration	For consideration	NG	NG	NG

Figure 5. (**a**) Illustration of preparation process; (**b**) comparison performance in dielectric inks in quality, appearance, and functionality. Green text indicates ”acceptable”; red text indicates “unacceptable”; blue text indicates “for consideration”.

During the selection stage, the cross-sectional analysis results on Dielectric A and Dielectric B deemed them as acceptable. Discoloration and cracks were found in Dielectric C where it touched the silver trace (Figure 6). Conductive trace thickness was found to be 9–10 µm and that of dielectric (×3) was 20.45–28 µm.

The reliability or absence of a short circuit in three printed layers each in either Dielectric A, Dielectric B, and Dielectric C was tested. The dielectric provides insulation in multilayer printed circuitry. When effective, there should not be any leakage of current between the conductive layer and the crossover layer. A short circuit was absent from samples printed in three layers of Dielectric A and Dielectric B, respectively (Table 2). Resistance measured between points on the conductive trace and the crossover indicates over-limit readings. A short circuit was, however, found in samples printed in three layers of Dielectric C, across points on the conductive trace and the crossover, indicating that the dielectric was not working.

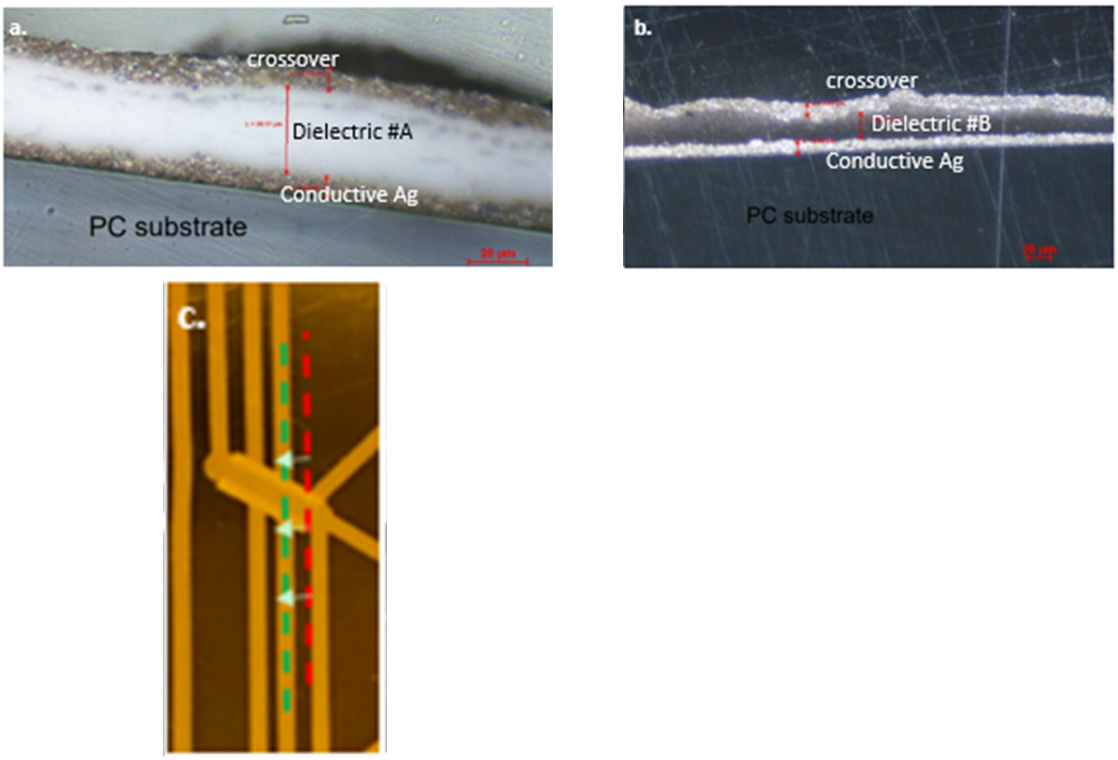
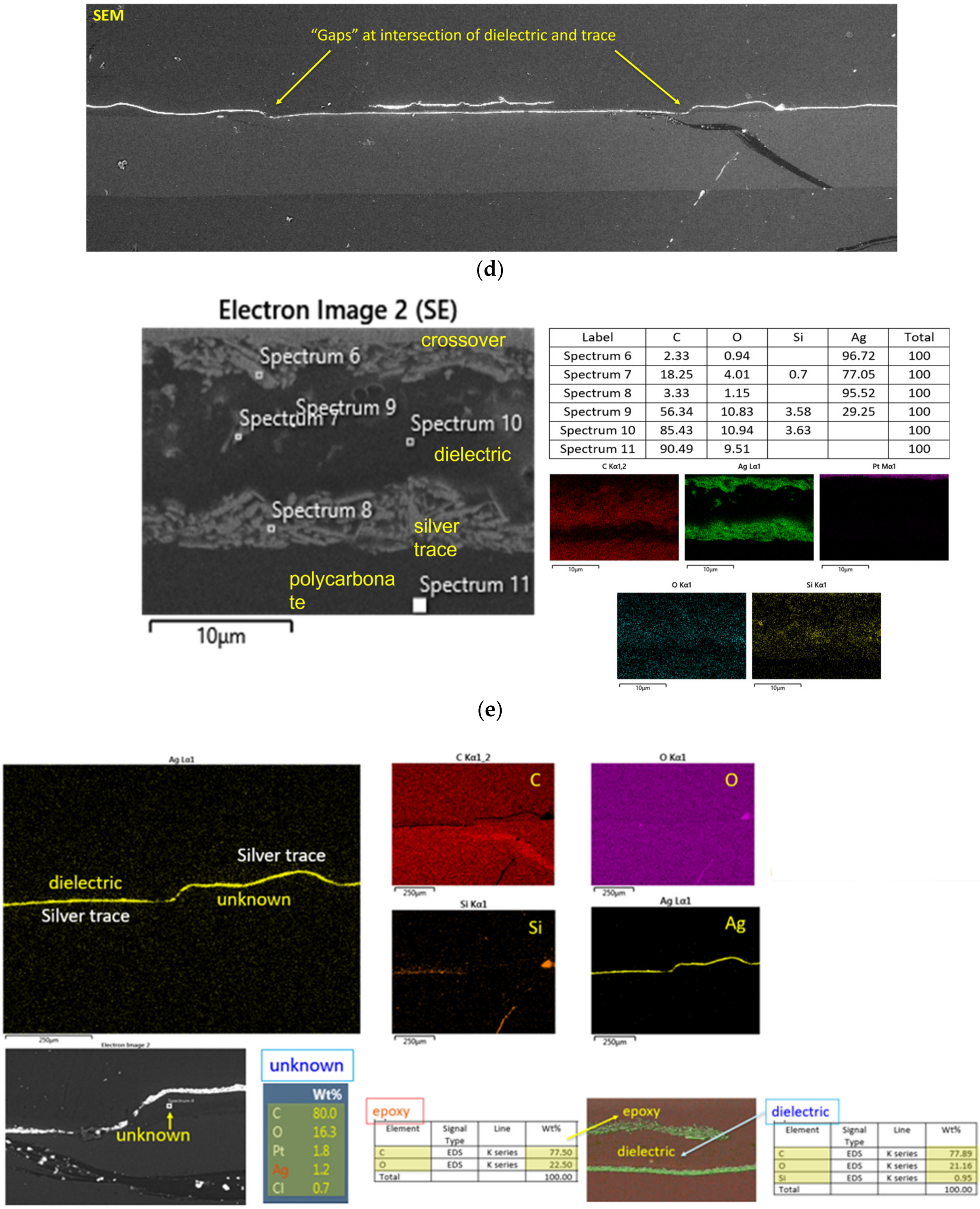


Figure 6. *Cont.*



(d)

Label	C	O	Si	Ag	Total
Spectrum 6	2.33	0.94		96.72	100
Spectrum 7	18.25	4.01	0.7	77.05	100
Spectrum 8	3.33	1.15		95.52	100
Spectrum 9	56.34	10.83	3.58	29.25	100
Spectrum 10	85.43	10.94	3.63		100
Spectrum 11	90.49	9.51			100

(e)

unknown

	Wt%
C	80.0
O	16.3
Pt	1.8
Ag	1.2
Cl	0.7

epoxy

Element	Signal Type	Line	Wt%
C	EDS	K series	77.50
O	EDS	K series	22.50
Total			100.00

dielectric

Element	Signal Type	Line	Wt%
C	EDS	K series	77.89
O	EDS	K series	21.16
Si	EDS	K series	0.95
Total			100.00

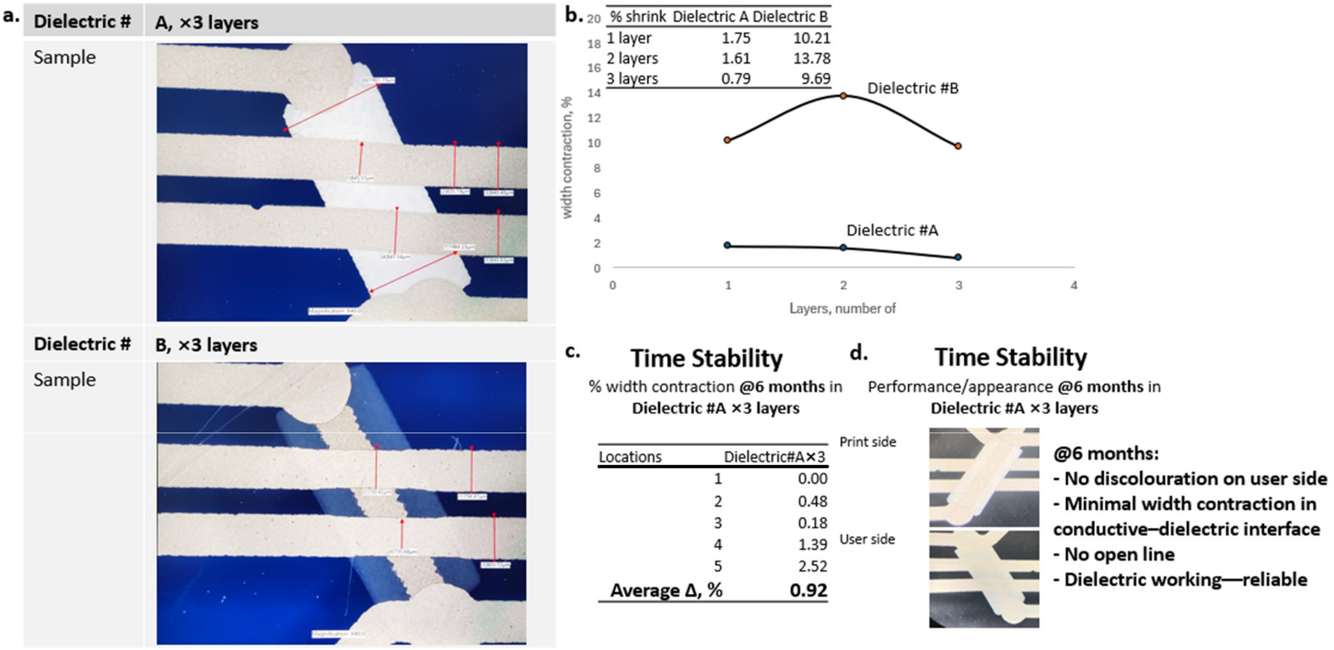
(f)

Figure 6. No delamination and no gap found at the intersection of dielectric ink and conductive trace in (**a**) Dielectric A or (**b**) Dielectric B. (**c**) Cross-sectioning position at the red line and polish at the green line. (**d**) Gap was found at the intersection of Dielectric C and the conductive trace; (**e**) silver was found to have seeped into the dielectric layer (Spectrums 7, 9). (**f**) "Gap" and thrusting of silver/delamination beyond the dielectric ink created an "unknown" area—analysis shows it is not Si-rich dielectric ink.

Table 2. Reliability of dielectrics at different thicknesses after elongation: (**a**) Dielectric A, (**b**) Dielectric B, and (**c**) Dielectric C.

a. Dielectric A				**b. Dielectric B**				**c. Dielectric C**			
Layers	A, ×1	A, ×2	A, ×3	Layers	B, ×1	B, ×2	B, ×3	Layers	C, ×1	C, ×2	C, ×3
A	Short circuit	No short circuit	No short circuit	A	Short circuit	Short circuit	No short circuit	A	Short circuit	Short circuit	Short circuit
B	Short circuit	Short circuit	No short circuit	B	Short circuit	Short circuit	No short circuit	B	Short circuit	Short circuit	Short circuit

Finally, the samples printed in one layer, two layers, and three layers each in Dielectric A and Dielectric B were measured using Keyence and the % width differences at five locations where the dielectric ink and conductive ink interacted (Figure 7).



% shrink	Dielectric A	Dielectric B
1 layer	1.75	10.21
2 layers	1.61	13.78
3 layers	0.79	9.69

Locations	Dielectric#A×3
1	0.00
2	0.48
3	0.18
4	1.39
5	2.52
Average Δ, %	**0.92**

@6 months:
- **No discolouration on user side**
- **Minimal width contraction in conductive–dielectric interface**
- **No open line**
- **Dielectric working—reliable**

Figure 7. (**a**) Samples printed in different dielectric types and thicknesses. (**b**) Width contraction % by dielectric thicknesses; (**c**) width % change in best performing dielectric at 6 months. (**d**) Appearance and performance of Dielectric A at 6 months.

In dielectric ink selection, the objective is to ensure that there is no current leakage across the top crossover layer and the bottom circuitry. A high volume of dielectric ink is the salient reason behind the bigger reactions observed between the conductive and the dielectric ink recipes causing seepage through the layers and discoloration and cracking of the traces due to the incompatibility of solvents and chemicals present in the inks. A good practice is to deposit a lower quantity of dielectric ink each time. In this case, we have found that screen-printing with a lower mesh thickness of 50–60 µm is optimal.

We have also found that to be effective, the total dielectric layer must be thick enough to act as an insulator between the conductive silver traces overlaid onto the polycarbonate substrate. In our study, printing three layers at 50–60 µm mesh thickness ensures reliability, and the thickness is found to be at least 20 µm using the best commercially available dielectric ink that we selected.

Finally, product samples were fabricated based on the above findings. Samples stayed functional after 100 h humidity test at 85 °C/85%RH, conditions in accord with the IPC-4203 standard [6].

4. Conclusions

This study explores a number of factors that must be addressed when selecting dielectric inks for implementing IME technology in the real world: firstly, the thickness of each deposition layer of dielectric ink and the total overall thickness of dielectric ink deposited were determined; secondly, evaluating the conductive–dielectric interface conditions and the reliability and repeatability at elongation. This study has derived that (1) to ensure optimal conductive–dielectric interface quality and reliability, there is a maximum quantity of dielectric ink allowed to be deposited each time. In this study, an optimal condition was achieved by depositing the selected commercially available dielectric ink with a 50–60 µm screen mesh; a higher deposition thickness at 110–120 µm gave rise to defects such as discontinuity and discoloration. (2) There is a minimum total thickness for which the dielectric would need to achieve insulation for preventing current leakage. In this study, this is found to be at least 20 µm of the selected commercially available dielectric ink. To ensure reliability, repeatability, and productivity in IME for real-world applications, the following are recommended: (i) the operating condition chosen needs to take into consideration the maximum elongation to ensure good quality of the dielectric trace, (ii) the deposition thickness chosen is a result of the amount of reaction between the dielectric and the conductive inks, (iii) the limitations of the current commercially available dielectric inks implies that other UV-curable dielectric inks may be considered for reduced curing time.

Author Contributions: Conceptualization, methodology, validation, resources, project administration, G.S.C.Y. and Y.M.T.; formal analysis, investigation, data curation, G.S.C.Y., P.H. and Y.M.T.; writing—original draft preparation, P.H.; writing—review and editing, P.H.; supervision, K.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is unavailable due to privacy.

Acknowledgments: We extend our sincere gratitude to SIMTech @A*STAR for the equipment, expertise, and resources rendered during the course of the project.

Conflicts of Interest: P.H. and K.W. were employed by the company DSBJ Pte Ltd. The remaining authors declare that the research was conducted in the absence of any potential conflict of interest.

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