LGJDX ISSN No: 1008-0562 Journal Of Liaoning Technical University Natural Science Edition

TECHNOLOGICAL INNOVATION SYSTEMS (TIS) AS ANALYSIS FRAMEWORK FOR TECHNOLOGY DIFFUSION IN DEVELOPING COUNTRIES: A CASE OF MALAYSIA

Hoo Kooi Lim[a], Seuk Wai Phoong[b], Ahmad Shuhaimi[c], Ainin Sulaiman[d]

[a]*Institute of Advanced Studies, Universiti Malaya, 50603 Kuala Lumpur, Malaysia*
[b]*Department of Decision Science, Faculty of Business and Economics, Universiti Malaya, 50603 Kuala Lumpur, Malaysia*
[c]*Low Dimensional Materials Research Centre (LDMRC), Department of Physics, Universiti Malaya, 50603 Kuala Lumpur, Malaysia*
[d]*Faculty of Business, International University Malaya-Wales, 50480 Kuala Lumpur, Malaysia*

Main author/Corresponding author: Hoo Kooi Lim
ORCID: https://orcid.org/0000-0002-7465-6921
Email: hookooi_lim@hotmail.com

Co-author: Seuk Wai Phoong
ORCID: https://orcid.org/0000-0002-9925-0901
Email: phoongsw@um.edu.my

Co-author: Ahmad Shuhaimi
ORCID: https://orcid.org/0000-0002-2575-850X
Email: shuhaimi@um.edu.my

Co-author: Aini Sulaiman
ORCID: https://orcid.org/0000-0002-8989-712X
Email: ainins@iumw.edu.my

Abstract

This study employs the Technological Innovation System framework to analyze the development and diffusion of gallium nitride technology in Malaysia. It investigates the role of key actors—government, industry, and academia in shaping the "direction of search" in advancing gallium nitride technology as a promising alternative to traditional silicon technology. The research highlights the strategic role of government initiatives, such as funding and incentives, in attracting industry investment and fostering university research aligned with market needs. Collaborative Research in Engineering, Science, and Technology Center served as a critical intermediary, facilitating stakeholder collaboration and accelerating innovation. The findings underscore the superior properties and potential applications of gallium nitride in 5G communication and power devices. A bidirectional relationship between government and industry, along with strong academia-industry partnerships, was essential in driving the progress of GaN technology in Malaysia. This study demonstrates how targeted government support and intermediaries can enhance technological capabilities in developing countries. By applying the TIS framework to a developing nation, the research provides insights into how Malaysia's approach to GaN technology could serve as a model for promoting innovation and economic growth. Additionally, it contributes to the broader understanding of the framework in developing nation contexts, offering valuable lessons for the nations that seeking to strengthen their high-tech industries, particularly in alignment with Malaysia's National Semiconductor Strategy.

Keywords: gallium nitride, technological innovation system, direction of search, intermediary

Statements and Declarations:

No funding was received for conducting this study. The authors have no relevant financial or non-financial interests to disclose.

1. Introduction

Technology is a key driver of economic development. Nations that prioritize technological advancements are better equipped to enhance their competitive advantage and attract multinational corporations to invest domestically (Chang and Hsu, 1998). Factors such as knowledge, workforce skills, and productivity are pivotal in attracting and retaining foreign direct investment (Monaghan, 2012). Domestic innovation and technology adoption shape long-term economic growth, with a country's investment in its own innovations driving its progress (Jiménez and Ziesemer, 2024).

In Malaysia, the electronics industry has been the cornerstone of the country’s exports and as a significant contributor to manufacturing value-added and employment since the 1970s. Multinational corporations have largely dominated electronics production and exports in Malaysia (Rasiah, 2013). During the 2000s, Malaysia's Electrical and Electronics (E&E) sector experienced a downturn as labour-intensive manufacturing operations relocated to neighbouring countries with larger economies of scale and lower production costs, such as China, Vietnam, and the Philippines (Chin et al., 2018). The Malaysian government recognized that the nation had reached a critical juncture in its economic development. With its traditional economic growth engine showing significant deceleration over the past decade, there emerged a pressing need for a new catalyst for growth (PEMANDU, 2010).

In response, the Malaysian government launched the Economic Transformation Program (ETP) in 2010, aiming to elevate the country to a high-income economy (NEAC, 2010). As part of the ETP, one of the entry point projects focused on enhancing the front-end operation of light-emitting diodes (LEDs), particularly in epitaxy, with gallium nitride (GaN) identified as a highly promising base material (EPU, 2014). In 2014, the "GaN-on-GaN Program" was initiated as a research and development (R&D) endeavor to bring GaN technology to Malaysia and reduce reliance on foreign suppliers for epitaxy (EPU, 2014).

GaN has emerged as one of the most promising semiconductor materials over the past two decades, garnering significant attention for its exceptional properties (Lam et al., 2023). As a wide bandgap semiconductor, GaN presents several advantages over conventional silicon, including higher breakdown voltage, superior thermal conductivity, and enhanced efficiency at high frequencies (Green et al., 2014). These attributes make GaN particularly suitable for power devices, which are critical across a range of applications, from consumer electronics to industrial systems (Ueda, 2014).

In recent years, Malaysia has successfully attracted significant foreign direct investment (FDI) from multinational companies, further cementing its position in the global semiconductor sector (Eltgen et al., 2020). The introduction of the Malaysia’s National Semiconductor Strategy underscores the nation’s commitment to strengthening its semiconductor industry and fostering innovation (Said and Tan, 2024).

This study applies the Technological Innovation System (TIS) framework, which was developed to analyze the evolution and advancement of emerging technologies (Hekkert et al., 2007; Bergek et al., 2008b). By adopting the systematic approach of the TIS framework, this research considers the actors, networks, and institutions involved in the development and diffusion of GaN technology in Malaysia. Specifically, it explores the factors influencing the "direction of search" in GaN’s technological advancement and dissemination. The study also highlights the critical intermediary role of Collaborative Research in Engineering, Science, and Technology Center (CREST), which accelerates the innovation process and enhances the effectiveness of the TIS in Malaysia’s GaN technology ecosystem. Furthermore, this research identifies key roles played by government, industry, and academia in shaping the direction of semiconductor technology. A deeper understanding of these influencing factors enables the policymakers to engage the relevant stakeholders and implement strategic measures in alignment with resource allocation, knowledge transfer, and skills development. This, in turn, can enhance Malaysia’s technological capabilities, foster economic growth, and position the country as a global leader in the semiconductor industry, in line with the recent announcement of Malaysia's National Semiconductor Strategy.

2. Literature review

2.1 Electrical and Electronics Industry in Malaysia

In 2010, the Malaysian government launched the ETP. with the aim of transitioning the country from a period of economic stagnation to a high-income economy (Hassan et al., 2016). As part of the ETP, the E&E sector was identified as one of the 12 National Key Economic Areas (NKEAs) crucial to Malaysia's economic revitalization. Within this sector, a specific entry point project was designated to enhance the front-end operations of LEDs (PEMANDU, 2010). GaN was highlighted as a critical semiconductor material for this initiative, particularly due to its application in epitaxial layers for LEDs (EPU, 2014).

In 2014, the Malaysian government embarked on the "GaN-on-GaN Program," allocating RM72 million over five years to foster the domestic development of GaN technology and diminish the nation's reliance on foreign epitaxy suppliers (Jacobs, 2017). This program was orchestrated by the CREST, a non-profit knowledge institute. CREST was tasked with facilitating the transfer of GaN technology from the University of California, Santa Barbara (UCSB) to local Malaysian universities (EPU, 2014).

In 2024, Malaysia unveiled its ambitious National Semiconductor Strategy, marking a significant milestone in the nation's journey towards becoming a key player in the global semiconductor industry (Lee & Teng). This comprehensive strategy aims to leverage Malaysia's established strengths in the E&E sector while addressing the challenges of an increasingly competitive and technologically advanced market. The strategy outlines a multi-pronged approach that includes investment in cutting-edge research and development, enhancement of manufacturing capabilities, and the cultivation of a highly skilled workforce adept in semiconductor design and fabrication (Said and Tan, 2024). Furthermore, the strategy emphasizes the importance of public-private partnerships and international collaborations to foster innovation and ensure access to global markets. With this strategic initiative, Malaysia aspires to not only fortify its position in the semiconductor supply chain but also to drive sustainable economic growth and technological advancement (Kaur, 2024).

2.2 Conceptual Framework

The TIS framework is employed to examine the development, diffusion, and adoption of new technologies. It focuses on understanding the dynamics and processes that shape technologies innovation and adoption of technologies within a specific context (Carlsson and Jacobsson, 1997; Hekkert et al., 2007; Bergek et al., 2008b). The TIS framework considers the interactions among various actors, networks, institutions, and infrastructures that drive technological advancements.

The key components of TIS are the actors, networks, institutions, and technological artifacts that constitute the structural factors making up the system (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2008a). Actors are the individuals, organizations, and institutions involved in the development and use of the technology. They include 1) firm: companies that produce, develop, or use the technology; 2) research institutions: universities, research laboratories, and other entities engaged in technological R&D; 3) government bodies: policymakers and regulatory agencies that create policies and regulations influencing the technology; 4) non-governmental organizations (NGOs): groups that may advocate for or against the technology based on its societal impacts; 5) users: end-users and consumers who adopt and utilize the technology. Networks are the connections and interactions between actors that facilitate the exchange of information, resources, and knowledge (Bergek et al., 2008b). Networks can include formal partnerships, collaborations, and informal relationships. Institutions are the rules, norms, and regulations that govern the behaviour of actors within the TIS (Bergek et al., 2008b). Institutions can be formal, such as laws and regulations, or informal, such as cultural norms and practices (Hekkert et al., 2007; Bergek et al., 2008a). Technological artifacts are the physical and knowledge-based components of the technology itself, including patents, prototypes, and technical standards (Das and Van de Ven, 2000).

LGJDX ISSN No: 1008-0562 Journal Of Liaoning Technical University Natural Science Edition

The TIS framework identifies several key functions that drive the innovation process. These functions help to assess the performance and development of the technological system. (Bergek et al., 2008a; Bergek et al., 2008c; Hekkert et al., 2007; Jacobsson and Bergek, 2011; Johnson & Jacobsson, 2001). They are 1) knowledge development and diffusion: the creation and dissemination of scientific and technical knowledge related to the technology; 2) influence on the direction of search: factors that guide the focus and priorities of innovation activities, such as market demand, societal challenges, and policy incentives; 3) entrepreneurial experimentation: activities undertaken by entrepreneurs to explore and develop new applications and business models for the technology; 4) market formation: the development of markets for the new technology, including creating demand and establishing market structures; 5) resource mobilization: the allocation and deployment of financial, human, and physical resources necessary for the development and diffusion of the technology; 6) legitimation: the process of gaining social acceptance and support for the technology, including addressing regulatory and societal barriers; 7) development of positive externalities: the generation of benefits beyond the immediate application of the technology, such as the creation of new industries, job opportunities, and societal benefits (Bergek et al., 2008a).

The TIS framework is widely used to analyze and facilitate the development of emerging technologies across various sectors (Palm, 2022). By examining the components and functions of a TIS, policymakers, researchers, and industry stakeholders can identify strengths, weaknesses, opportunities, and threats to the innovation process (Wieczorek and Hekkert, 2012). This analysis can inform strategies to foster technological innovation, enhance competitiveness, and achieve economic and societal objectives (Carlsson and Stankiewicz, 1991).

The TIS framework is a commonly used analytical tool for studying the development and diffusion of emerging technologies (Hekkert et al., 2007). However, TIS research has largely focused on developed countries, rarely being applied to developing countries. Notably, the TIS framework has limitations when applied to developing countries unless it is modified in a way that better considers their specific contexts (Edsand, 2019).

3. Methodology

This study employs a qualitative research methodology to examine the current status and development of GaN technology in Malaysia, focusing on the “direction of search” function. A qualitative approach is appropriate for capturing the complex and contextual factors (Birkinshaw et al., 2011) shaping GaN technology’s evolution, providing in-depth insights into the interactions between key stakeholders (Yauch and Steudel, 2003). Semi-structured interviews (Stake, 2005) were conducted with representatives from government agencies, technology experts, university researchers, and representatives from industries involved in GaN technology. Purposive sampling (Yin, 2009) was used to select participants with relevant expertise, including those from government agencies, research institutions, industry associations, and leading semiconductor companies. An interview guide with open-ended questions was developed to explore the “direction of search”. This flexible format (Creswell, 2012). allowed for follow-up questions and deeper exploration of the topics discussed. By using this qualitative method, the study captures the nuanced factors influencing GaN technology development in Malaysia

4. Results and Discussions

In this paper, the focus is on one of the functions of the TIS: influence on the direction of search and the role of "intermediaries" which makes the TIS framework applicable in the context of a developing country.

4.1 Influence on the Direction of Search

The influence on the direction of search within a TIS pertains to the ways in which various actors within the system can guide technological R&D activities (Carlsson and Stankiewicz, 1991; Geels, 2004; Hekkert et al., 2007; Suurs, 2009). This influence manifests in several forms, including the determination of funding allocations, the fostering of collaborations and partnerships, the prioritization of research areas, responses to market demands, addressing societal needs, and capitalizing on technological opportunities (Bergek et al., 2008a).

This section examines the factors that shape the direction of search in the context of developing and diffusing GaN technology in Malaysia. These factors are influenced by the strategic decisions of various actors within the innovation system, which can significantly impact the orientation of R&D activities. The data analysis under the function of "influence on the direction of search" has revealed three main factors:

i. Technology Trajectory;
ii. Mutual Influence Among the Government, Industry, and Local Universities;
iii. Emerging and Future Technologies

These factors collectively shed light on the intricate dynamics that have guided the trajectory of the development and diffusion of GaN technology in Malaysia. As shown in Figure 1, longstanding technologies have reached their limits for multiple applications, and the technology trajectory points to a shift toward the development of new technologies—in this case, GaN technology. GaN technology has undergone its own distinct development path. Emerging technologies have incorporated GaN as one of their base materials due to its inherent advantages over traditional materials (e.g., silicon). In the context of the development and diffusion of GaN technology in Malaysia, the influence of industry actors has been dominant, exerting influence on the government and its "institutional and policy context" to invest in the technology and universities to build up the country's "scientific and technical knowledge." The Malaysia government has offered significant incentives to attract the industry to invest in GaN technology in Malaysia.

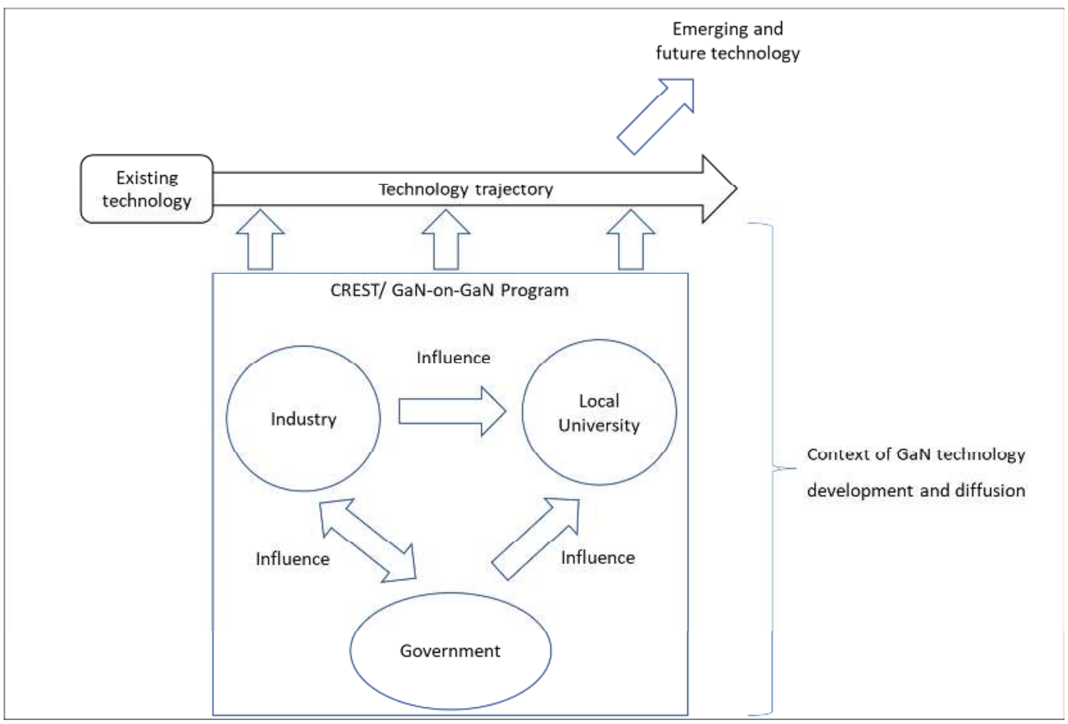

Figure 1 Influence on the Direction of Search in the Context of Malaysia (Source: Author)

4.1.1 Technology Trajectory

In the context of the development and diffusion of GaN technology, all interviewees agreed that silicon technology has reached its performance limits and unanimously recognized GaN as the next generation semiconductor material. The wide bandgap nature of GaN was underscored, with its material properties receiving particular emphasis. These properties include an expansive energy bandgap, elevated breakdown voltage, and enhanced capabilities for high-frequency switching when compared to silicon. Such characteristics make GaN suitable for power devices and RF applications.

> *"Gallium nitride technology is an example of a compound semiconductor technology and, in many ways, is one of the most advanced compound semiconductor technologies […] [We are starting to] see compound semiconductors start to take over many applications currently [occupied] by silicon or [to be used] alongside silicon. [This is happening] because of reasons of speed, efficiency, plus the ability to implement new functionality, which is not possible using silicon." (Industry #1)*

> *"Gallium nitride is enabling a new generation of power devices that can exceed the performance of silicon-based devices due to its unique electronic properties." (Academia #2)*

> *"So, as companies move from silicon to gallium nitride […] you can tell silicon technology—you can consider it is fully mature right now, and [it] probably is approaching a limit [in terms of its] capability already." (Government #2)*

> *"As we know, silicon technology is approaching its limit. So, gallium nitride technology has demonstrated that capability to be [a] replacement technology for silicon semiconductors in power conversion, RF, and analog applications." (CREST #2)*

In summary, the shift from silicon to GaN technology represents a significant transformation in the semiconductor industry, driven by the limitations of silicon in certain applications. GaN's superior properties—such as higher breakdown voltage, greater thermal conductivity, faster frequency response, and higher power density—make it a compelling alternative (Lam et al., 2023). This transition is not only technological but also strategic, positioning Malaysia to lead in semiconductor innovation. The positive trajectory of GaN adoption reflects a successful recognition of, and response to, these technological opportunities. However, the shift toward GaN technology requires continuous monitoring and adaptation to emerging trends. Strategic investments in GaN R&D could firmly establish Malaysia as a leader in the global semiconductor market.

4.1.2 Mutual Influence Among the Government, Industry, and Local Universities

This factor illustrates the significant collaborative efforts among industry, government, and university stakeholders.

(i) Influence Between the Industry and Government

The industry plays a pivotal role in steering the prioritization of technologies for further development (Fabbri et al., 2018). In the context of the development and diffusion of GaN technology in Malaysia, one interviewee from the industry (Industry #1) highlighted the industry's proactive involvement in addressing the semiconductor industry's gaps. However, the leadership in this search was provided by Malaysia's Performance Management and Delivery Unit (PEMANDU), established by the government in 2009 to oversee the execution of national transformation programs. In the LED sector, consensus between industry and government officials pinpointed epitaxy as a critical gap, despite its status as the most value-added segment of the LED supply chain. Feedback from industry participants underscored the importance of epitaxy, prompting its strategic inclusion as one of the 12 National Key Economic Areas (NKEAs) in the ETP, specifically under EPP #8: "Developing LED Front-End Operations" (PEMANDU, 2010).

"[In] the semiconductor world, there was a recognition that, although Malaysia was very strong in assembly and the testing of opto semiconductors, it was weak at both chip fabrication and what's called the epitaxy level, which is the front side of the value chain of opto semiconductors […] So, PEMANDU recognized that there was a gap, an area [that would need to be addressed] if Malaysia wanted to participate in the full value chain of optic semiconductors […] So, something like the PEMANDU group [needed to engage with the] industry and build roadmaps." (Industry #1)

Furthermore, the government provided incentives to stimulate investment from industry stakeholders in GaN technology within Malaysia. In response, foreign direct investment (FDI) has played a pivotal role in Malaysia's remarkable economic expansion, contributing not only through capital growth but also via the transfer of technology and expertise to the developing nation (Bakar et al., 2022; Hamood et al., 2018). The strategic deployment of government incentives as a catalyst for introducing GaN technology to the country was underscored by multiple interviewees.

"The incentives [that the] industry would get if it invests in Malaysia […]. Yes, I do—of course, speaking for my company specifically—yes. I believe others have also got that opportunity. So, I believe the door is open." (Industry #1)

"It's been a challenge, but I think we made a big breakthrough through the fab of [the company], [through which] they transferred the epi into Malaysia, and that is not a straightforward kind of decision from [the company]. It went through a series of discussions with MIDA and we have to [hold up] our offer and also incentives to make the deal." (Government #1)

The factors that have steered the direction of search in the development and diffusion of GaN technology in Malaysia are twofold: (1) the industry's pivotal role in pinpointing epitaxy as a strategic area, thereby shaping government policy, and (2) the government's strategy of offering incentives to spur industry investment in GaN technology. This dynamic illustrates a case of bidirectional influence, where both the industry and the government exert mutual impact on each other's actions.

(ii) Influence Between the Industry and Local Universities

Collaborations between the private sector and universities are well-established in developed regions such as Europe and North America, where universities possess comprehensive infrastructures capable of conducting R&D to support industry needs (Roncancio-Marin, 2022). In Malaysia's development and diffusion of GaN technology, the data suggests that local universities have not been the driving force; rather, it is the industry that has been propelling universities to focus on GaN technology research through the GaN-on-GaN Program. All three industry participants expressed the following:

"We have—let me be blunt—we have forced the universities to stick with one topic and see it through […] for the first few years. They were not motivated or impressed by that because they felt there were easier things to be done elsewhere. But I think now they see the value. So, the value is the quality of their publications, the depth of their work, the international involvement they can have. I think they really realize they have put hard work in their works." (Industry #1)

LGJDX ISSN No: 1008-0562 Journal Of Liaoning Technical University Natural Science Edition

“That's why, in CREST, we have set up an industry steering committee. So, there are some people overseeing the research [to ensure quality].” (Industry #2)

“If you look at the US, you can see that the model is quite successful because they can come to the universities. They have people supporting this—for example, Silicon Valley—they have many professors. When they ran into problems and so on, they know who to get, where to get help, and so on. They also have those equipment builders, those materials companies in the US to provide that kind of knowledge. Unfortunately, over here, we don't have that ecosystem. We are far from them, but we need to work on that. We need to close the gap.” (Industry #3)

The collaboration between industry and local universities has underscored the necessity for academia to revise its norms and practices in scientific research (Lam, 2010). This entails identifying and adhering to best practices to forge and maintain such collaborations (Awasthy et al., 2020). The findings reveal that Malaysian universities are predominantly responsive to the industry's guidance regarding the direction of GaN technology research, necessitating close collaboration with industry partners in pertinent research domains.

(iii) Influence Between the Government and Local Universities

Government funding can act as a lever to influence and foster innovation (Song et al., 2022). In the case of GaN technology's development and diffusion in Malaysia, the government allocated RM 72 million to enhance knowledge and capabilities in GaN technology at Malaysian universities through the GaN-on-GaN Program.

“Let’s [look at] the academic perspective for the moment. So, you can imagine that when the government has initiative in this aspect, the university will start to have professors or the academics will start to look into this topic.” (Academia #1)

“I think the government has shown strong support for the technology through the gallium nitride-on-gallium nitride national program, [through which] RM 72 million has been allocated to bring gallium nitride-on-gallium nitride technology to this country.” (Academia #2)

“Funding from the government approved by EPU for the value-management lab report was RM 72 million.” (Government #2)

“We managed to raise from the government […] about 72 million ringgits […] as well as contributions from the local companies as well as contributions from the universities to get this program started.” (CREST #1)

Typically, government funding is a decisive factor in guiding the direction of research (Song et al., 2022). The Malaysian government has bolstered the development and diffusion of GaN technology by financing the establishment of laboratories at local universities, which included procuring new equipment, materials, and access to fabrication and characterization services. This financial support has not only advanced GaN research at these institutions but has also aligned with the needs of the industry.

In summary, the bidirectional influence between industry and government plays a crucial role in steering the direction of search. The industry's identification of epitaxy as a strategic area prompted government incentives, which, in turn, spurred further industry investment in GaN technology. This symbiotic relationship highlights the importance of collaboration and mutual responsiveness in driving technological advancements.

Similarly, the industry’s influence on local universities emphasizes the need for academia to adapt to evolving industry demands. This responsiveness ensures that academic research remains relevant and aligned with market needs, fostering both innovation and practical applications of GaN technology. The identification and adoption of best practices in collaboration further strengthen these partnerships, enhancing the overall innovation ecosystem.

Policies and incentives should be designed to promote sustained collaboration between government, industry, and academia. Academic institutions must remain agile and responsive to industry needs to ensure the continued relevance and impact of their research.

4.1.3 Emerging and Future Technology

GaN has emerged as the cornerstone material for an array of emerging and future technologies. Its applications span across power devices (Zhong et al., 2022), 5G communication devices (Ding et al., 2022), LiFi systems (Raring et al., 2022), UVC LEDs for the neutralization of the COVID-19 virus (Yao et al., 2022), micro-LED displays (Smith et al., 2020), wireless charging units (Kumar et al., 2020), and heterogeneous integration (Hsu, 2021), to name a few. The vast majority of study participants highlighted the significant potential of GaN across these diverse domains.

> *“The opportunity is to bring these two technologies together, recognizing that gallium nitride can't do everything but also [that] silicon can’t do everything. […] a combination of these technologies creates new opportunities, new products, that address new market needs. So, that's a great opportunity. The topic in general is called heterogeneous integration, the integration of these two different technologies. That will become very hot in the next five to ten years.” (Industry #1)*

> *“I think we are talking about 5G technology in communication. And [it] definitely is using gallium nitride technology for this. And other than that, smartphones also now [use it for] facial recognition, especially with this COVID-19, facial recognition, location tracing. All these need high-speed data and big data. I believe gallium nitride technology can provide this. And other than that, we hope the technology can also be used for agriculture, aquaculture, telecommunication, automotive, and also biotechnology.” (Government #2)*

> *“For communication, 5G is the fastest way now. But the laser LiFi is maybe five or six orders higher than 5G. This LiFi will be very important for wireless communication [because] gallium nitride today is a very, very important material for wireless communication, fiber communication, lighting, health, etc.” (Academia #3b)*

> *“The emerging areas that we are looking at [are] gallium nitride [for] power devices, gallium nitride for communications devices—for example, 5G, microLED, lasers, UV LED, etc.” (CREST #1)*

In summary, GaN has been widely recognized as a fundamental material crucial to the advancement of a wide range of emerging and future technologies (Lam et al., 2023). Its exceptional properties make it indispensable for power devices, 5G communication, LiFi systems, UVC LEDs, micro-LED displays, wireless charging, and more. These applications are central to the GaN technology roadmap, shaping the future of innovation in this sector.

The study participants consistently emphasized the significant potential of GaN, particularly in driving technological breakthroughs. Heterogeneous integration, which combines GaN with silicon, is expected to create new opportunities and products, addressing evolving market needs over the next five to ten years. GaN's role in high-speed communication technologies, such as 5G and beyond, is seen as transformative, with applications extending into industries like agriculture, aquaculture, automotive, and biotechnology.

Furthermore, the potential of GaN in laser-based LiFi, which promises performance several magnitudes faster than 5G, reinforces its importance in the future of wireless communication. The strong industry-government-academia collaboration around GaN R&D is expected to play a critical role in sustaining the momentum of innovation and establishing GaN as a cornerstone material for global technological advancements.

4.2 Intermediaries

Intermediaries have emerged as significant players by accelerating the innovation process and enhancing the effectiveness of the TIS. Intermediaries also act as catalysts in fostering collaboration among multiple parties across various phases of the innovation process (De Silva et al., 2018). The adoption of intermediaries in eco-innovation efforts has been observed in Sweden, Germany (Kanda et al., 2019), and the United States (Gliedt, 2018).

In the context of the development and diffusion of GaN technology in Malaysia, CREST played an intermediary role. This intermediary role is made clear which revealed how CREST formulated a proposal and successfully secured funding from the Malaysian government. Moreover, CREST established an oversight committee comprising industry, academia, and government representatives (as well as some from CREST itself) with an industry expert assuming leadership. This strategic move by CREST facilitated effective communication and collaboration among various stakeholders and entities engaged in the advancement and dissemination of GaN technology, thereby promoting more efficient knowledge sharing and knowledge transfer. Furthermore, CREST played a pivotal role in the establishment of research laboratory facilities at UM and USM.

> *"That is why, in CREST, we have set up an industry steering committee. So, there are some people who oversee that the research is good." (Industry #2)*

> *"CREST put […] together, and so on, and then got the EPU, which is the government, to go through. I am happy that the government looked at it and approved […] the funding for it." (Industry #3)*

> *"We managed to raise from the government […] about 72 million ringgits […] as well as contributions from the local companies as well as contributions from the universities to get this program started." (CREST #1)*

> *"We have two mirror labs from UCSB located at UM and USM. These two labs are equipped with full capability for gallium nitride growth and characterization through the gallium nitride-on-gallium nitride program." (CREST #2)*

In summary, intermediaries like CREST play a pivotal role in driving innovation and fostering collaboration. The CREST-led GaN-on-GaN Program has served as a collaborative platform through which various stakeholders could collaborate to promote the development and diffusion of GaN technology in Malaysia They build and enhance the networks of key actors—be they government entities, universities, or companies—in TISs. As a result, they accelerate the development and diffusion of technologies, ultimately advancing technological progress.

5.0 Conclusions

This study, through the application of the TIS framework, has provided valuable insights into the development and diffusion of GaN technology in Malaysia. The findings reveal that the limitations of silicon technology in certain applications served as a catalyst for the industry to identify GaN as a promising alternative, prompting active government involvement. The government, primarily through initiatives like PEMANDU, offered incentives to attract industry investment in GaN technology, reinforcing a mutually beneficial relationship between the public and private sectors.

Key actors—government, industry, and academia. Each played distinctive roles in advancing GaN technology, with universities responding to industry demands through research aligned with market needs. The government's financial support, particularly in the form of funding laboratories and providing resources, facilitating the development of GaN technology in accordance with industry expectations. This support not only strengthened Malaysia's position in the semiconductor field but also ensured that the country remained competitive in global technology markets.

A significant finding of the study is the role of intermediaries like CREST, which played a pivotal role in accelerating innovation by fostering collaboration between government, academia, and industry. By enhancing communication and cooperation among these key actors, CREST made substantial contributions to the TIS, speeding up the development and diffusion of GaN technology.

The successful development and diffusion of GaN technology in Malaysia, as analyzed through the TIS framework, serves as a valuable case study for understanding how emerging technologies can be nurtured in developing countries. This research also highlights the importance of targeted government support, strong industry-academic partnerships, and effective intermediaries in fostering technological innovation. The insights gained from Malaysia's experience with GaN technology offer important lessons for other developing nations seeking to close the technological gap and position themselves as leaders in high-tech industries.

Furthermore, the study contributes to the broader understanding of TIS in developing countries.It demonstrates how the framework can be applied to analyze technological advancement and innovation systems in such contexts. The findings provide both theoretical and practical contributions, offering a model for policymakers and stakeholders to enhance Malaysia's technological capabilities and drive sustainable economic growth, particularly in the semiconductor industry, in alignment with the country's National Semiconductor Strategy.

7.0 Future Works and Limitations

While this study primarily focused on the early stages of GaN development and diffusion in Malaysia, particularly emphasizing the "direction of search," it also highlighted the need for further research in several other areas. The findings provide a foundation for future research endeavors. Specifically, while this study examined the "influence on the direction of search" within the TIS framework, future research should explore other critical functions, such as "resource mobilization", "knowledge development and diffusion", "entrepreneurial experimentation," "market formation," "legitimation," and the "development of positive externalities." A more comprehensive understanding of these functions could promote sustainable innovation, help bridge the technological gap in Malaysia, and ultimately contribute to the country's economic growth and development.

References

Awasthy, R., Flint, S., Sankarnarayana, R., & Jones, R. L. (2020). A framework to improve university–industry collaboration. Journal of Industry-University Collaboration, 2(1), 49-62. https://doi.org/10.1108/JIUC-09-2019-0016

Bakar, A. H. A., Sinnappan, P., Salim, F. A. A., & Teo, P. C. (2022). Factors influencing foreign direct investment (FDI) location selection: a review of the literature. International Journal of Academic Research in Business and Social Science, 12(7), 1271-1291. http://dx.doi.org/10.6007/IJARBSS/v12-i7/14103

Bergek, A., Jacobsson, S., & Hekkert, M. (2008b). Functions in innovation systems: A framework for analysing energy system dynamics and identifying goals for system-building activities by entrepreneurs and policy makers. In Foxon, T., Köhler, J., & Oughton, C. (Eds.), Innovation for a Low Carbon Economy: Economic, Institutional and Management Approaches, (pp.79–111). Edward Elgar.

Bergek, A., Jacobsson, S., & Sandén, B. A. (2008c). 'Legitimation' and 'development of positive externalities': two key processes in the formation phase of technological innovation systems. Technology Analysis & Strategic Management, 20(5), 575-592. https://doi.org/10.1080/09537320802292768

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008a). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy, 37(3), 407-429. https://doi.org/10.1016/j.respol.2007.12.003

Birkinshaw, J., Brannen, M. Y., & Tung, R. L. (2011). From a distance and generalizable to up close and grounded: Reclaiming a place for qualitative methods in international business research. Journal of International Business Studies, 42, 573-581. https://doi.org/10.1057/jibs.2011.19

Carlsson, B. & Jacobsson, S. (1997). In search of a useful technology policy-general lessons and key issues for policy makers. In Carlsson, B. (Ed.), Technological Systems and Industrial Dynamics, 10, (pp. 299-315). Springer Science & Business Media.

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. Journal of Evolutionary Economics, 1, 93-118. https://doi.org/10.1007/BF01224915

Chang, P. L., & Hsu, C. W. (1998). The development strategies for Taiwan's semiconductor industry. IEEE Transactions on Engineering Management, 45(4), 349-356.

Chin, Y. W., Lim, K. T., Khoh, S. B., & Kamaruddin, S. (2018). Knowledge and Talent Development in the Electronics and Electrical (EE) Industry of Malaysia: State-Industry-University Collaboration. Asian Journal of Social Science, 46(6), 668-705. https://doi.org/10.1163/15685314-04606004

Creswell, J. W. (2012). Qualitative Inquiry and Research Design: Choosing among Five Approaches (3rd ed.). Sage.

Das, S. S., & Van de Ven, A. H. (2000). Competing with new product technologies: A process model of strategy. Management Science, 46(10), 1300-1316. https://doi.org/10.1287/mnsc.46.10.1300.12276

De Silva, M., Howells, J., & Meyer, M. (2018). Innovation intermediaries and collaboration: Knowledge–based practices and internal value creation. Research Policy, 47(1), 70-87. https://doi.org/10.1016/j.respol.2017.09.011

Ding, S., Kou, L., & Wu, T. (2022). A GAN-based intrusion detection model for 5G enabled future metaverse. Mobile Networks and Applications, 27(6), 2596-2610. https://doi.org/10.1007/s11036-022-02075-6

Economic Planning Unit (EPU). (2014). Projek Kerjasama Gallium Nitride on Gallium Nitride (GaN-on-GaN) Antara CREST dan University of California Santa Barbara (UCSB), Makmal Pengurusan Nilai. Value Management Lab (VML). Collaborative Research in Engineering, Science & Technology.

Edsand, H. E. (2019). Technological innovation system and the wider context: A framework for developing countries. Technology in Society, 58, 101150. https://doi.org/10.1016/j.techsoc.2019.101150

Eltgen, M. P., Liu, Y., & Chong, Y. K. (2020). Malaysia: Attracting superstar firms in the electrical and electronics industry through investment promotion. An Investment Perspective on Global Value Chains, 276-299.

Fabbri, A., Lai, A., Grundy, Q., & Bero, L. A. (2018). The influence of industry sponsorship on the research agenda: a scoping review. American Journal of Public Health, 108(11), e9-e16. https://doi.org/10.2105/AJPH.2018.304677

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy, 33(6-7), 897-920. https://doi.org/10.1016/j.respol.2004.01.015

Gliedt, T., Hoicka, C. E., & Jackson, N. (2018). Innovation intermediaries accelerating environmental sustainability transitions. Journal of Cleaner Production, 174, 1247-1261. https://doi.org/10.1016/j.jclepro.2017.11.054

Green B., Moore K., Hill D., Debaca M.C., Schultz J., Noori B., Bokatius M. (2014). Gallium nitride RF technology advances and applications, Edicon-China 2014.

Hamood, M. A. S., Pandurengan, M. M., & Kalam, K. K. (2018). Foreign direct investment determinants in Malaysia. British Journal of Business Design & Education, 11(1), 1-16.

Hassan, M. G., Abdullah, R., & Razalli, M. R. (2016). Measuring Outsourcing Performance of Malaysian Economic Transformation Program. International Journal of Business & Management Science, 6(1).

Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change, 74(4), 413-432. https://doi.org/10.1016/j.techfore.2006.03.002

Hsu, L. H., Lai, Y. Y., Tu, P. T., Langpoklakpam, C., Chang, Y. T., Huang, Y. W., & Chang, E. Y. (2021). Development of GaN HEMTs fabricated on silicon, silicon-on-insulator, and engineered substrates and the heterogeneous integration. Micromachines, 12(10), 1159. https://doi.org/10.3390/mi12101159

Jacobs, J. (2017, May 19). Science & Innovation: White light and blue LED dreams. The Edge Malaysia. https://theedgemalaysia.com/article/science-innovation-white-light-and-blue-led-dreams

Jacobsson, S., & Bergek, A. (2011). Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environmental Innovation and Societal Transitions, 1(1), 41-57. https://doi.org/10.1016/j.eist.2011.04.006

Jiménez, J. R. P., & Ziesemer, T. H. (2024). Technology adoption, innovation policy and catching-up. Economic Change and Restructuring, 57(2), 60.

Johnson, A., & Jacobsson, S. (2001). Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden. Technology and the Market: Demand, Users and Innovation, 89-111.

Kanda, W., del Río, P., Hjelm, O., & Bienkowska, D. (2019). A technological innovation systems approach to analyse the roles of intermediaries in eco-innovation. Journal of Cleaner Production, 227, 1136-1148. https://doi.org/10.1016/j.jclepro.2019.04.230

Kaur, D. (2024). Malaysia unveils 3-phase US$5.3bil National Semiconductor Strategy to strengthen position in all-out global semicon war. https://www.digitalnewsasia.com/digital-economy/malaysia-unveils-3-phase-us53bil-national-semiconductor-strategy-strengthen-position

Kumar, K., Banerjee, S., & Kumar, R. R. (2020, December). Efficiency analysis of a 7.4 kW dynamic wireless charging system for electric vehicle through GaN devices. In 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES) (pp. 1-6). IEEE. https://doi.org/10.1109/PEDES49360.2020.9379565

Lam, A. (2010). From 'ivory tower traditionalists' to 'entrepreneurial scientists'? Academic scientists in fuzzy university—industry boundaries. Social Studies of Science, 40(2), 307-340. https://doi.org/10.1177/0306312709349963

Lam, W. H., Lam, W. S., & Lee, P. F. (2023). The studies on gallium nitride-based materials: A bibliometric analysis. Materials, 16(1), 401.https://doi.org/10.3390/ma16010401

Lee, E & Teng L.J. (2024). Cover Story: National Semiconductor Strategy to guide industry up value chain. https://theedgemalaysia.com/node/714965

Monaghan, S. (2012). Attraction and retention of foreign direct investment (FDI): The role of subnational institutions in a small, highly globalised economy. Irish Journal of Management, 31(2), 45.

National Economic Advisory Council (NEAC) (2010), New Economic Model For Malaysia Part 1, Secretary, National Economic Advisory Council.

Palm, A. (2022). Innovation systems for technology diffusion: An analytical framework and two case studies. Technological Forecasting and Social Change, 182, 121821. https://doi.org/10.1016/j.techfore.2022.121821

Performance Management and Delivery Unit (PEMANDU). (2010). Economic Transformation Programme: A Roadmap for Malaysia. Prime Minister's Department.

Raring, J. W., Rudy, P., Goutain, E., Sztein, A., Melo, T., Van Den Broeck, D., & Lee, C. (2022, May). High-Power GaN-based Laser Diodes for Next Generation Applications. In Proceedings of the International Conference on Compound Semiconductor Manufacturing Technology (CS MANTECH 2022), Monterey, CA, USA (pp. 9-12).

Rasiah, R. (2013). Are electronics firms in Malaysia catching up in the technology ladder?. In Innovation and Industrialization in Asia (pp. 82-100). Routledge.

Roncancio-Marin, J., Dentchev, N., Guerrero, M., Díaz-González, A., & Crispeels, T. (2022). University-Industry joint undertakings with high societal impact: A micro-processes approach. Technological Forecasting and Social Change, 174, 121223. https://doi.org/10.1016/j.techfore.2021.121223

Said, F., & Tan, A. (2024). Malaysia's semiconductor ecosystem amid geopolitical flux. https://www.isis.org.my/wp-content/uploads/2024/06/Malaysia%C2%80%C2%99s-semiconductor-ecosystem-amid-geopolitical-flux.pdf

Smith, J. M., Ley, R., Wong, M. S., Baek, Y. H., Kang, J. H., Kim, C. H., Gordon M. J., Nakamura S., Speck J. S. & DenBaars, S. P. (2020). Comparison of size-dependent characteristics of blue and green InGaN microLEDs down to 1 μ m in diameter. Applied Physics Letters, 116(7). https://doi.org/10.1063/1.5144819

Song, Y., Sahut, J. M., Zhang, Z., Tian, Y., & Hikkerova, L. (2022). The effects of government subsidies on the sustainable innovation of university-industry collaboration. Technological Forecasting and Social Change, 174, 121233. https://doi.org/10.1016/j.techfore.2021.121233

Stake, R. E. (2005). Qualitative Case Studies. In Denzin N. K. & Lincoln Y. S. (Eds.), The Sage Handbook of Qualitative Research (pp. 443-466). Sage.

Suurs, R. A. (2009). Motors of Sustainable Innovation: Towards a Theory on the Dynamics of Technological Innovation Systems. [Unpublished doctoral dissertation]. Utrecht University.

Ueda, T., Ishida, M., Tanaka, T., & Ueda, D. (2014). GaN transistors on Si for switching and high-frequency applications. Japanese Journal of Applied Physics, 53(10), 100214. https://doi.org/10.7567/JJAP.53.100214

Wieczorek, A. J., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Science and Public Policy, 39(1), 74-87. https://doi.org/10.1093/scipol/scr008

Yao, Y., Zollner, C. J., Wang, M., Iza, M., Speck, J. S., DenBaars, S. P., & Nakamura, S. (2022). Polarization-enhanced p-AlGaN superlattice optimization for GUV LED. IEEE Journal of Quantum Electronics, 58(4), 1-9. https://doi.org/10.1109/JQE.2022.3159821

Yauch, C. A., & Steudel, H. J. (2003). Complementary use of qualitative and quantitative cultural assessment methods. Organizational Research Methods, 6(4), 465-481. https://doi.org/10.1177/1094428103257362

Yin, R. K. (2009). Case Study Research (4th ed.). Sage.

Zhong, Y., Zhang, J., Wu, S., Jia, L., Yang, X., Liu, Y., Zhang, Y. & Sun, Q. (2022). A review on the GaN-on-Si power electronic devices. Fundamental Research, 2(3), 462-475. https://doi.org/10.1016/j.fmre.2021.11.028