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GALLIUM NITRIDE TECHNOLOGY AS A CATALYST FOR MALAYSIA'S ECONOMIC GROWTH

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Abstract

This study explores the development and diffusion of gallium nitride (GaN) technology in Malaysia, employing the Technological Innovation System (TIS) framework to analyze resource mobilization and its impact on economic growth. Through a case-study approach, the research examines the roles of government funding, collaboration, human capital development, and physical infrastructure in advancing gallium nitride technology. The findings highlight the pivotal role of government investment, with RM 72 million allocated to the Gallium Nitride-on-Gallium Nitride (GaN-on-GaN) Program, facilitating technology transfer and local capability development. Collaborative efforts among universities, industry, and government entities optimized resource distribution, driving innovation and economic progress. The study underscores the importance of human capital, with a significant increase in the number of researchers specializing in GaN technology has enhanced Malaysia's attractiveness to foreign direct investment. The establishment of fully equipped laboratories at Universiti Malaya and Universiti Sains Malaysia marked a crucial step in promoting technological innovation. The adoption of gallium nitride technology supports the light-emitting diode value chain in Malaysia, significantly boosting export value and positioning the country as a competitive player in the global light-emitting diode industry. The insights gained from this case study offer valuable lessons for technology adoption in developing countries, demonstrating the effectiveness of the technological innovation system framework in such contexts. Despite limitations in scope, the research lays the groundwork for future studies on other technological innovation system functions, contributing to a deeper understanding of technology-driven economic development. This study serves as a model for leveraging technological advancements to enhance national development and attract investment.

Keywords: gallium nitride, technological innovation system, resource mobilization, economic growth

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1. Introduction

Technology is a cornerstone of economic development, driving growth through various channels. In developing countries, the lack of advanced technology and knowledge often hampers economic progress, while developed nations thrive on innovation, continuously creating cutting-edge technologies. The transfer of technology from developed to developing nations is a crucial process that can significantly enhance economic prospects (World Bank, 2008). This transfer can occur through mechanisms such as foreign direct investment (FDI), international partnerships, and collaborative research initiatives (Jaumotte et al., 2013). By facilitating access to advanced technologies, developing countries can improve productivity, foster innovation, and accelerate their economic development (Chang and Hsu, 1998). Understanding the prioritization of resource mobilization is essential for policymakers and stakeholders seeking to drive economic growth, as it requires a thorough assessment of existing capabilities, the potential for scaling up, and positioning within the broader technology value chain growth (Yongabo, P., & Göktepe-Hultén, 2021).

Malaysia, a developing country that gained independence in 1957, initially relied heavily on agriculture before transitioning to manufacturing in the 1970s (Rasiah, 2013). However, by the 2000s, the nation's economic growth had slowed as manufacturing operations shifted to lower-cost regions like China (Chin et al., 2018). In response, the Malaysian government launched the Economic Transformation Program (ETP) in 2010 to revitalize the economy (PEMANDU, 2010). One of the focal points of this initiative, known as the National Key Economic Area (NKEA), is the Electrical and Electronics (E&E) sector, with a particular emphasis on advancing frontend light-emitting diode (LED) technology. A key project within this sector aims to establish epitaxial capabilities for LED production in Malaysia, focusing on Gallium Nitride (GaN), a crucial semiconductor material for LEDs (EPU, 2014).

Historically, Malaysia's involvement in the LED industry has been limited to assembly and testing, with companies like Hewlett Packard (HP) and Siemens Electronics (now known as Osram) establishing operations in the country since the 1970s (Jacobs, 2017; Tan, 2017). Despite this presence, there has been little research or industrial activity in the epitaxial process, which is essential for frontend LED production. To accelerate learning and technological development, Malaysia initiated a collaboration with the University of California, Santa Barbara (UCSB) in 2014, launching the GaN-on-GaN program (MIDA, 2014). This initiative aims to develop GaN epitaxial capabilities within Malaysia, positioning the country to become a significant player in the global LED industry.

This study employs the Technological Innovation System (TIS) framework to explore the transfer and development of GaN technology from UCSB to Malaysian universities, specifically the Universiti Malaya (UM) and Universiti Sains Malaysia (USM). The first objective is to analyze resource mobilization by assessing the allocation and utilization of financial, human, and infrastructural resources critical for advancing GaN technology in Malaysia. The study also examines how GaN technology enhances Malaysia's economic growth, particularly through increased export value and FDI.

This research contributes to a deeper understanding of resource mobilization in the context of emerging technologies, using the development of GaN technology in Malaysia as a case study. Additionally, the study demonstrates how targeted technological development can serve as a catalyst for economic growth—particularly through enhanced export value—providing valuable insights for policymakers aiming to harness innovation for national development.

2. Literature Review

2.1 Technological Innovation Systems

This study proposes the use of Technological Innovation Systems (TIS) to understand the development and diffusion of new technologies. The TIS framework is a systemic approach that considers the complex interactions between various actors, institutions, and processes that shape the innovation process (Bergek et al., 2008b; Carlsson and Jacobsson, 1997; Hekkert et al., 2007).

2.1.1 Key Features of a TIS

The key components of a TIS are the actors, networks, and institutions that constitute the structural factors making up the system (Bergek et al., 2008a; Carlsson and Stankiewicz, 1991; Hekkert et al., 2007). Relevant actors include technology manufacturers, suppliers, universities, research institutes, associations, regulators, venture capitalists, private and public firms, government agencies, and non-governmental organizations (NGOs). Networks are formed from the connections and interactions among actors with similar interests, making joint impacts or contributions toward the development of a TIS. These networks are primarily inter-organizational, including user-supplier networks, university-industry networks for knowledge exchange, political networks, or advocacy coalitions aimed at solving specific tasks or influencing institutions (Bergek et al., 2008b). Institutions consist of formal entities, such as regulations, industry standards, and legislation, and informal entities, such as social norms, routines, user practices, and cultures (Bergek et al., 2008a; Hekkert et al., 2007). All these components contribute to and influence the overall function of developing, diffusing, and utilizing new products and processes.

2.1.2 TIS Functions

Scholars have suggested using a set of key processes—referred to as system functions—as performance indicators to analyze TIS performance (Bergek et al., 2008a; Bergek et al., 2008c; Jacobsson and Bergek, 2011; Hekkert et al., 2007). There are numerous sets of system functions, indicating that the TIS framework is still evolving and that ongoing revisions will be necessary as the comprehension of system functions continues to advance (Bergek et al., 2008b). This study adopts the list of system functions outlined by Bergek et al., as shown below in Table 1: i) knowledge development and diffusion, ii) influence on the direction of search, iii) entrepreneurial experimentation, iv) market formation, v) resource mobilization, vi) legitimation, and vii) development of positive externalities (Bergek et al., 2008a).

TABLE 1 TIS FUNCTIONS

System Functions	Description
F1—Knowledge development and diffusion	This function encompasses the process of creating, developing, exchanging, and diffusing technological knowledge within the system.
F2—Influence on the direction of search	This function assesses the level of influence on actors (e.g., firms, organizations) to become part of a TIS and actively engage in its development. This also entails exploring various competitive technologies, markets, applications, and organizational models.
F3—Entrepreneurial experimentation	This function encompasses the entrepreneurial activities primarily originating from the private sector within a TIS. Entrepreneurs or actors within the system continually learn and adapt, gaining valuable insights with which to navigate the dynamic landscape of technological innovation.
F4—Market formation	This function revolves around the creation of new markets within a TIS, particularly for emerging technologies that have the potential to develop and flourish.
F5—Resource mobilization	This function pertains to the availability of human capital and financial resources to facilitate the development of a TIS. Financial resources include grants for research and development (R&D) projects, capital investment for product development and commercialization activities, and complementary assets such as

	infrastructure, facilities, services, and networks, all of which contribute to the growth and success of the system.
F6—Legitimation	This function entails the process of enabling technology by legalizing and making it socially acceptable within a societal context. The growth of an emerging technology often faces opposition from parties with vested interests in existing technologies. In such situations, advocacy coalitions can play a crucial role as catalysts by promoting the legitimacy of the emerging technology.
F7—Development of positive externalities	This function operates in conjunction with the other six functions within a TIS. It entails the generation of positive externalities through the strengthening of other functions, reflecting the collective outcomes of the TIS process. New entrants in an emerging TIS play a crucial role in driving positive externalities.

2.2 GaN as a Fundamental Material for LEDs

Gallium Nitride (GaN) is a III-V compound semiconductor widely used in LEDs since the 1990s. It is one of the most promising materials for LEDs' epitaxial films, which are the source of their emitted light. Its direct wide band gap of 3.39 eV (Akasaki, 2002) affords it special properties to produce blue, violet, and ultraviolet LEDs. Blue is unique in that it can create white light, which is the main market for lighting (Jacobs, 2017).

GaN was first investigated as a potential material for LEDs in the late 1960s by Paul Maruska and Jacques Pankove at the Radio Corporation of America (RCA) and was later considered by Isamu Akasaki and his colleagues at Nagoya University in Japan and by Shuji Nakamura at Nichia Corporation (Pimputkar et al., 2009). The first breakthrough in growing GaN involved the use of GaN nucleation layers for high-quality GaN growth on foreign material—specifically sapphire (Al2O3) (Nakamura, 1991). The second breakthrough involved the activation of p-type conductivity in GaN doped with Mg using post-growth anneal (Nakamura, et al., 1992). These breakthroughs led to the development of the first high-efficiency blue LED device in 1993 (The Japan Times, 2002) and, subsequently, the generation of white light using blue LEDs.

The LEDs produced using GaN began to evolve in the 2000s and started to replace traditional lighting technologies, including incandescent and compact fluorescent lighting (DenBaars, 2013). Thus, GaN represents the most attractive material for research on next-generation energy-efficient electronics. Additionally, GaN has advantages over silicon devices in terms of higher power density, faster switching speeds, and wider bandgap. These advantages have attracted researchers to begin employing this material in high-power and high-radio-frequency devices (Ueda, 2014).

2.3 Initiative of GaN Technology in Malaysia

EPP #8, "Developing LED Front-End Operations," is one of the key Entry Point Projects (EPPs) under the E&E NKEA (PEMANDU, 2010). GaN epitaxy has been recognized as the primary material for LED front-end operations (EPU, 2014). EPP #8 is led by the Ministry of International Trade and Industry (MITI) and the Malaysia Investment Development Authority (MIDA), supported by the Ministry of Science, Technology, and Innovation (MOSTI), the Penang Development Corporation, and the Northern Corridor Implementation Authority (NCIA). MIDA set out in 2010 to target LED front-end operations and bring at least one GaN epitaxy manufacturer to Malaysia by 2014; this effort was expected to create cluster synergies and bring in high-value-added jobs, such as epitaxy engineer positions (PEMANDU, 2010).

On December 18th, 2014, the MIDA CEO announced a collaboration with UCSB focused on GaN epitaxy development called the Gallium Nitride-On-Gallium Nitride (GaN-on-GaN) Program. This program was a joint initiative involving local academic institutes (Universiti Sains Malaysia (USM), Universiti Malaya (UM), Universiti Malaysia Perlis (UniMAP), and Monash University Malaysia), industry actors (various LED manufacturers in Malaysia), and government entities under the leadership of Collaborative Research in Engineering, Science, and Technology (CREST) (MIDA, 2014). On November 11th, 2015, Germany-based Osram announced an investment of one billion euros to build a new LED chip plant in Kulim, Malaysia. The MIDA CEO stated that this project would be beneficial to the country by promoting job creation and strengthening the overall LED ecosystem in Malaysia (The Star, 2015).

3.0 Methodology

This research employs a case-study method to gain a nuanced understanding of the development and diffusion of GaN technology within a systemic context (Creswell and Poth, 2018). By accessing a complex network of actors, including government entities, local universities, industry stakeholders, and UCSB, this approach facilitates a deeper exploration of network dynamics, influences on the direction of search, government policy, and resource mobilization.

The study adopted a comprehensive approach to data collection, encompassing semi-structured interviews and document reviews. Semi-structured interviews were conducted to elicit descriptions and interpretations from participants, allowing for the exploration of diverse perspectives (Stake, 2005). A total of 12 respondents were selected from the GaN-on-GaN Program's network of actors, including government agencies, private-sector companies, local universities, UCSB researchers, and CREST employees who contributed to the program. These interviews provided a diverse pool of perspectives and a rich body of data.

Documents, as tangible artifacts such as reports, policies, letters, emails, and campaign memos, were reviewed to provide a detailed understanding of the complex social phenomenon (Crossley and Vulliamy, 1997). The documents reviewed included past records documenting links between various parties involved in the GaN-on-GaN Program.

The data analysis process began by identifying key elements derived from both interviews and documents. Data underwent initial coding, resulting in categories and subcategories that served as the basis for further analysis and the formulation of detailed concepts. Subsequently, the data were systematically mapped according to themes. Before engaging in in-depth data analysis, a coding scheme was established to organize the collected text. This scheme aligned the interview transcripts and documents with the research questions and theoretical framework. The research entailed the analysis of 12 interview transcripts and 78 pertinent documents, including the GaN-on-GaN Program Oversight Committee's meeting minutes, contracts with stakeholders, and UCSB principal investigator visiting reports.

Conventional content analysis was employed to describe the phenomenon (Hsieh and Shannon, 2005; Miles and Huberman, 1994). The analysis process unfolded iteratively, with data undergoing three rounds of review to refine and harmonize emerging themes. This iterative approach allowed for a thorough exploration of thematic highlights, ensuring alignment with the research questions.

4. Results and Discussions

This paper focuses on one of the functions of the TIS: resource mobilization, and how GaN technology contributes to the country's economy, particularly in terms of export value, within the context of a developing country.

4.1 Resource Mobilization

Resource mobilization, defined as the availability and use of human and financial resources to facilitate the successful development and diffusion of a specific technology, plays a crucial role in the success of a TIS (Bergek et al., 2008b). This section addresses the research question with a specific focus on resource mobilization aimed at promoting the development and diffusion of GaN technology in Malaysia. Through data analysis, four themes have emerged under the broader theme of "resource mobilization":

i. Theme 1 – Funding
ii. Theme 2 – Collaboration
iii. Theme 3 – Human capital development and investment
iv. Theme 4 – Physical infrastructure

Human resources can be mobilized through education and training in specialized technological fields, while financial resources encompass various sources, such as grants for R&D projects, capital investments, and commercialization activities, as well as tangible assets like infrastructure. Figure 1 illustrates the process of resource mobilization in the context of the development and diffusion of GaN technology in Malaysia. Government funding is the essential component behind promoting GaN technology in the country. The funding is channelled through the CREST-led GaN-on-GaN Program, which functions as a collaborative platform bringing together the Malaysian government, industry, and local universities alongside UCSB to develop human capital and build up the physical infrastructure to support the development of GaN technology. Human capital significantly influences the decisions of multinational LED companies regarding investment in a developing country like Malaysia.

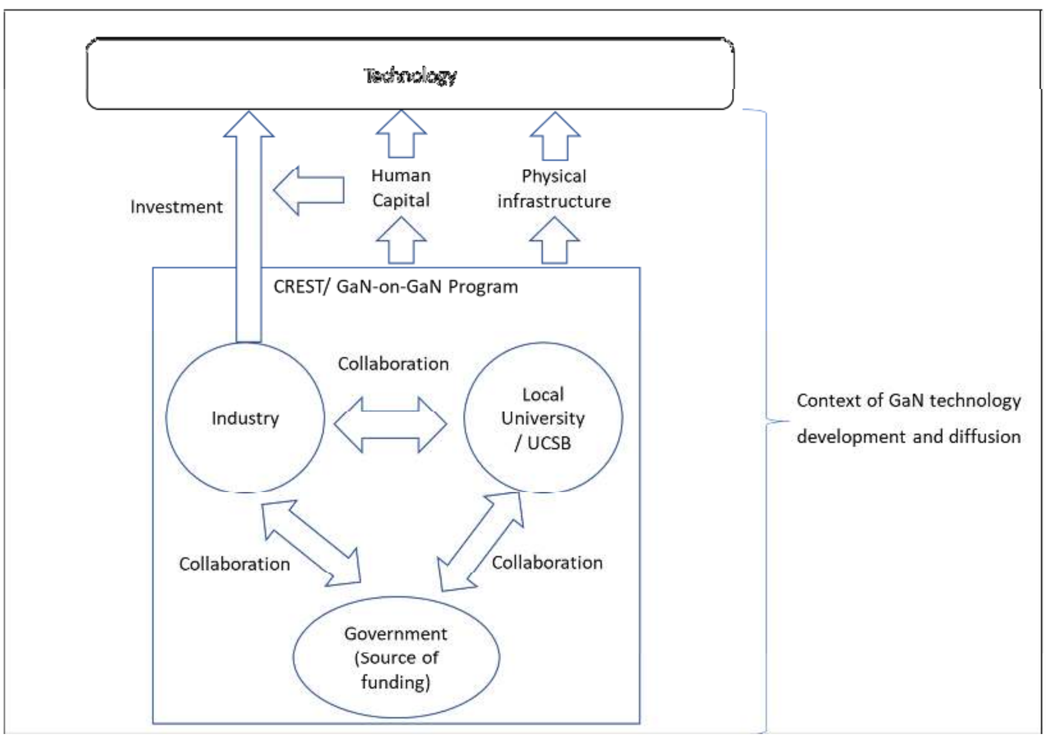

Figure 1: Resource Mobilization in the Context of the Development and Diffusion of GaN Technology (Source: Author)

4.1.1 Funding

(a) *Interview Results*

In the context of the development and diffusion of GaN technology, all interviewees highlighted that the government allocated a total of RM 72 million through the GaN-on-GaN Program:

"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 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)

When it comes to high-cost and high-tech projects, government funding plays a critical role as a catalyst and support mechanism. Several participants referenced Chinese government initiatives to make their point:

"[...] China subsidized all equipment put into China by 50%. And if you bought a MOCVD machine, they paid [for] half of it."(Academia #3a)

"China has sponsored one MOCVD (which is the key [piece of] equipment for gallium nitride technology) for every one MOCVD purchase by the manufacturer from year 2008 until 2018."(CREST #2)

The Malaysian government also offered subsidies to attract FDI, including incentives offered by MIDA:

"It is not a straightforward kind of decision to have [company] transfer the epi manufacturing to Malaysia. 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)

"MIDA, for example, is now promoting gallium nitride epitaxy investments in the country by offering incentives for prospective companies to set up in Malaysia. MIDA is the key investment promoter for the country."(CREST #1)

(b) *Document Findings*

Government funding plays a crucial role in driving technology innovation (Song et al., 2022). The Malaysian government allocated a total of RM 72 million under Rancangan Malaysia Ke-10 (RMK-10) and Rancangan Malaysia Ke-11 (RMK-11) between 2015 and 2020 to promote the development and diffusion of GaN technology. The funding was primarily channelled to the GaN-on-GaN Program and utilized for various purposes (EPU, 2014). The government financial support was provided over multiple years in tranches, demonstrating the government's commitment to the development and diffusion of GaN technology in the country. The funding was used for (1) Transfer of GaN-on-GaN technology (characterization, fabrication, packaging, and analytics) from the UCSB to Malaysia; (2) Sending researchers to UCSB, direct involvement in the establishment of metal organic chemical vapor deposition (MOCVD) in Malaysia to bring the level of research in Malaysia; (3) Renovation, installation of MOCVD at CREST and USM, equipping laboratories with the necessary equipment, as well as equipment contributions from the industry and academia; (4) Procurement of materials needed to carry out research activities; (5) Hiring of human resources, research, and administration; and (6) Managing intellectual property.

(c) ***Discussions***

The allocation of RM 72 million by the Malaysian government to the GaN-on-GaN Program underscores the critical role of public funding in advancing technological innovation. This substantial investment facilitated the transfer of GaN technology from UCSB to Malaysia, enabling the development of local capabilities and infrastructure. The strategic use of government funds not only supported the acquisition of essential equipment and materials but also fostered collaboration among universities, industry, and government entities. This approach mirrors successful international models, such as Taiwan. This is evident from the history of silicon, for which government funding and assistance constituted a key initiating factor in Taiwan back in the 1970s (Chang and Hsu, 1998). The Malaysian government's commitment to funding high-tech projects highlights its recognition of the importance of technology as a driver of economic growth and its willingness to invest in initiatives that promise long-term benefits for the national economy.

4.1.2 Collaborations

Collaboration between universities, companies, and the government can optimize resource allocation and connectivity, fostering innovation and economic growth (Schmieder-Ramirez, 2023).

(a) ***Interview Results***

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, including through resource mobilization. It is supported by the interviews with a participant who is currently service in a government agency.

"The total project cost, basically, was 116 million. Out of this 116 million, 72 million was funded by the government. The balance of the 116 million minus 72 million […] was funded by the universities and […] the industry players."(Government #2)

(b) ***Document Findings***

The CREST-led GaN-on-GaN Program has served as a collaborative platform for a diverse range of stakeholders—including academia, industry, and government actors—all working together to drive the development and diffusion of GaN technology in Malaysia. This was highlighted in the VML report, which documented the forecasted contributions from universities and companies (EPU, 2014). This collaboration was exemplified by the active engagement of multiple stakeholders with CREST. Additionally, the industry's provision of chip components to local universities was instrumental in initiating their research endeavors. Notably, the significant financial contributions from UM and USM to the program underscore the collaborative spirit between academic institutions and industry actors within the program.

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"[The industry] will provide [a] singulated chip for UniMAP to start the activities."(Document #31)

"[…] total actual contributions from UM to the program [amount to] over the 5 years […] the contributions from USM to the program [amount to] from 2016–2020."(Document #51)

(c) *Discussions*

Collaboration among academia, industry, and government actors can maximize resource distribution and connectivity, driving innovation and economic growth (Schmieder-Ramirez, 2023). The collaborative framework established by the GaN-on-GaN Program exemplifies the power of partnerships in driving technological advancement. By bringing together diverse stakeholders, including academia, industry, and government, the program created a platform for resource sharing and joint problem-solving. This collaborative approach not only optimized resource allocation but also facilitated the exchange of knowledge and expertise, accelerating the development and diffusion of GaN technology in Malaysia. The active engagement of universities and industry actors in the program underscores the importance of building synergies between research and practical application. Such collaborations are essential for fostering innovation and ensuring that technological advancements translate into tangible economic benefits. The program's success in mobilizing contributions from various parties highlights the potential of collaborative efforts to overcome challenges and achieve shared goals.

4.1.3 Human Capital Development and Investment

"Human capital" refers to a workforce equipped with relevant knowledge and skills. It plays a critical role in driving economic growth and development by enhancing productivity and enabling the utilization of technological advancements (Abbas et al., 2022).

(a) *Interview Results*

GaN technology was invented and used as the base material for white LEDs in the 1990s (Pimputkar, 2009). Around 2000, there were no people in Malaysia working on GaN research. This is supported by one of the informants, that

"When I came back to Malaysia in 1998, nobody in the country was doing work on gallium nitride-based materials and devices."(Academia #2)

The number of researchers rose steadily over the course of the five-year program. More than 50 researchers in Malaysia were working on GaN technology research. It is supported by insights gathered through the following interviews.

"[There are] more than 50 researchers across UM, USM, UniMAP, Monash, and UCSB. We have three Malaysian PhD students."(Government #2)

"The gallium nitride-on-gallium nitride program has grown [to house] about 50 researchers across UM, USM, UniMAP, Monash, and UCSB. At UCSB, we have three Malaysian PhD students."(CREST#2)

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Human capital is a factor that investors behind FDI heavily consider, as highlighted by the industry participants:

"You know, when a multinational company is considering where to invest in technology and manufacturing, the availability of talent is one of the key measures of a site. So, in other words, there is no point in investing in a company with whatever cheap infrastructure and good government support. You know, [you need] talent available to actually execute the technology."(Industry #1)

"There are two reasons why investors [go] offshore. One is because of costs, and second, because of talent, right? Yeah, if our cost structure is too low, so, but if the talent is not there, then they will not come. Likewise, if [the cost structure] is too high […] and we have the talent, they might come to do some R&D […] only, but not the manufacturing—just how it will be. So, it's good that we have this talent prepared."(Industry #3)

(b) *Document Findings*

Universities have mobilized their resources by providing candidates for research programs as part of collaborations with other actors. Notably, there are now over 50 researchers specializing in GaN technology in Malaysia, underscoring the nation's research capacity and expertise in this field.

"University to provide CREST with candidates to participate in research program and/or sending to UCSB"(Document #2)

"There are total >50 GaN researchers in Malaysia."(Document #49)

(c) *Discussions*

Human capital development emerged as a pivotal factor in the success of the GaN-on-GaN Program. The significant increase in the number of researchers specializing in GaN technology reflects the program's effectiveness in building local expertise and capacity. By investing in education and training, the program equipped the workforce with the skills necessary to support the growth of the GaN industry. Human capital and FDI are interconnected (Abbas et al., 2022). This focus on human capital is crucial for attracting FDI, as multinational companies prioritize locations with a skilled labor force. The program's emphasis on developing human capital aligns with global trends, where talent availability is a key determinant of investment decisions. The interconnectedness of human capital and FDI underscores the need for continuous investment in education and training to sustain technological progress and economic growth.

4.1.4 Physical Infrastructure

The availability of physical infrastructure (e.g., research facilities, laboratories, equipment) is important for innovation activities (Wonglimpiyarat, 2023). Mobilizing physical infrastructure entails investments in building new facilities, upgrading existing ones, or sharing resources across different organizations. The third sub-theme to emerge from the transcript and document analysis was "physical infrastructure," under the theme of "resource mobilization."

(a) *Interview Results*

The GaN-on-GaN Program established two GaN research laboratories—one at UM and the other at USM, respectively—using government funding.

"Basically, both UM and USM right now, they have one MOCVD each for them to do the research." (Government #2)

"Currently, we have two mirror labs. With the assistance of UCSB, we set up the mirror labs at UM and USM. They are both capable of gallium nitride growth and characterization through the GaN-on-GaN Program." (CREST #1)

(b) *Document Findings*

Since the program's inception, CREST pursued approvals for equipment procurement to advance epitaxy and fabrication capabilities at local universities, prompting the universities to renovate their laboratories to accommodate the equipment. As a result, both UM and USM now possess fully equipped research facilities in which to conduct GaN research. These actions represent investments in physical infrastructure to support R&D in the field of GaN technology.

"CREST sought approval for the purchase of equipment needed by UM to have a full epitaxy and fabrication process." (Document #8)

The 4" high temperature MOCVD located in USM was fully commissioned on 22-Mar'18. (Document #31)

2 world-class lab[s] working on GaN research [at] UM and USM respectively. (Document #54)

(c) *Discussions*

Innovation labs can serve as effective catalysts for developing innovation capacity within organizations (Schiuma and Santarsiero, 2023). The establishment of fully equipped research laboratories at UM and USM represents a significant investment in physical infrastructure, essential for supporting innovation activities. These facilities provide the necessary environment for conducting advanced R&D in GaN technology, enabling Malaysia to position itself as a competitive player in the global LED industry. The government's role in funding and facilitating the creation of these labs highlights the importance of infrastructure in fostering technological innovation. By providing state-of-the-art equipment and resources, the program ensures that researchers have the tools needed to explore new frontiers in GaN technology. This investment in infrastructure not only enhances research capabilities but also attracts international collaborations and partnerships, further strengthening Malaysia's position in the technology value chain.

4.2 How Does GaN Technology Contribute to Malaysia's Economy?

This exploration is crucial, as technology has been at the core of economic growth and development since the Industrial Revolution (Cirera et al., 2022). In Taiwan, for example, silicon technology has been instrumental in driving the chip manufacturing industry and fueling economic growth over the last decade (Bi et al., 2022). In the context of Malaysia, GaN technology has been identified as a catalyst for national economic transformation within the framework of the country's ETP (EPU, 2014).

LED technology was invented in Malaysia in the 1970s, making it one of the country's pioneering industries. Several companies, such as Hewlett Packard (HP) and Siemens Electronics (now known as Osram), initially focused on LED packaging assembly and testing, with fabrication following suit in 2008. GaN epitaxy was entirely imported until 2017. This is an important detail because, in the LED value chain, GaN—one of the main materials used in epitaxial technologies—represents the majority of the added value (Jacobs, 2017).

Throughout the interview sessions, various participants highlighted the contributions of GaN technology to Malaysia's economy. The epitaxy process holds a higher value relative to fabrication, assembly, and testing. The doubling of export value since 2017 is primarily attributed to GaN technology.

"Before that, although billions of LED devices were assembled in Malaysia, all of those epitaxies are imported, so the value add in Malaysia was low. Now, as a result of this investment and the whole impact of the program, we now have a significant proportion of total output in locally fabricated chips and locally performed epi. And, as a result, the value-added in Malaysia is now very high. So, in terms of export value, of course, the total export value [has] increased." (Industry #1)

"If you are in the electronics industry, […] vertically upstream is actually the way to generate better incomes for the company. And one way of getting higher on the income level is to have control over the material technology because, ultimately, electronics [are effectively] circuits and materials. So, if you go upstream on the material system and you can [make] a significant footprint in that space, you have a chance to build an industry that escapes this major income trap." (Industry #2)

"Especially now that we have epi and fab, [those] will reduce the reliance on imports. So, there is more value added to the exports. Because if you look at it, sometimes they only look at the end product costs and at the prices to calculate the actual value—but how much value added is being done with epi and wafer? [They] definitely can help to increase that significantly." (Government #1)

*"Based on the *MATRADE reports, there was significant growth, ~2x for LED, in 2017—mainly contributed by the epitaxy process in Malaysia." (CREST #2)*

** Malaysia External Trade Development Corporation (MATRADE) is the national trade promotion agency tasked with developing and promoting Malaysia's exports to the global market.*

The empirical evidence indicates that export-led growth offers significant economic benefits. Exports directly contribute to a country's gross domestic product (GDP) (Dutt et al., 2009). Additionally, exporting has indirect effects on economic growth by improving resource allocation, increasing productivity, and advancing technology (Pan and Nguyen, 2018). Historically, Malaysia's LED industry has relied heavily on the extensive assembly and testing of LED devices and imported epitaxies, limiting the country's value-added. However, the adoption of GaN technology has resulted in a noticeable increase in export values, playing a vital role in completing the country's LED value chain. Furthermore, domestically manufactured LEDs are associated with the highest value-added prices (Reese et al., 2020). Collectively, these factors underscore the importance of a well-developed LED industry in Malaysia, as it has not only contributed to national economic growth but also facilitated the localization of the LED value chain, enhancing the country's economic prospects.

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On top of that, the 50 researchers specializing in GaN technology mentioned in section 4.1.3 also represent a significant pool of human capital, making the sector an attractive magnet for FDI in Malaysia. This built-up human capital stands as a crucial factor among prospective investors considering investment opportunities in Malaysia:

Developing countries with substantial levels of human capital, meaning those characterized by an educated population and a skilled labor force, tend to be more successful in attracting FDI (Abbas et al., 2022). FDI plays a significant role in promoting economic growth in such developing countries, which often face a lack of advanced technology, unoptimized managerial practices, and an underdeveloped financial system. FDI promotes economic growth by increasing capital inflows, creating jobs, expanding exports, and facilitating technology transfer (Liang et al., 2021). In Malaysia, FDI has consistently played a crucial role as the primary driver of total approved investments in the manufacturing sector in recent years. In 2022, the manufacturing sector maintained its status as the country's leading recipient of FDI, with the E&E sector specifically emerging as the top investment with RM 27.9 billion—42.3% of Malaysia's total FDI that year (MIDA, 2022). The insights from industry experts underscore the critical role of human capital in corporations' evaluation of investment opportunities. This factor holds more significance than, for example, cost or infrastructure. Multinational companies invest in technology and manufacturing facilities when they identify an appropriate corresponding workforce. This shared perspective indicates that the availability of human capital is a critical factor in attracting investment and catalyzing economic growth.

5.0 Conclusion

In conclusion, resource mobilization was a crucial aspect of the development and diffusion of GaN technology in Malaysia. Government funding played a pivotal role in initiating technology transfer, developing local capabilities, and procuring the necessary equipment and materials. Without such financial support, the promotion of GaN technology in Malaysia would have been far more challenging and likely far less successful. Collaboration between universities, industry, and the government maximized resource distribution and connectivity, driving innovation. Various stakeholders leveraged their strengths to advance technological progress and economic development in the country. The mobilization of resources significantly contributed to the development of human capital in GaN technology, which proved to be a critical factor for multinational companies, such as Osram, in their investment decisions. The establishment of fully equipped laboratories at UM and USM marked a crucial step in promoting technological innovation in GaN technology in the country.

LED technology originated in Malaysia in the 1970s. Despite this, for several decades, the country focused on LED packaging and testing, only adding fabrication capabilities in 2008. However, the epitaxy process is far more beneficial in terms of value added compared to fabrication, assembly, and testing within the LED value chain. Until 2017, Malaysia relied entirely on imported epitaxy. Thus, the adoption of GaN technology marked a significant turning point for the country, as it completed the LED value chain within the country and led to a notable increase in its overall export value.

Furthermore, the readiness of GaN technology enhances the country's attractiveness to FDI, in large part due to the associated rise in the country's human capital. Multinational companies invest in technologies and manufacturing facilities that are accompanied by an appropriately skilled workforce, meaning that the availability of human capital is a crucial factor in attracting investment and, in turn, catalyzing economic growth.

The insights gained from the Malaysian case study can serve as a valuable example of technology adoption within the TIS framework in the context of a developing country. It is essential to recognize that the application of TIS in developing countries is relatively uncommon (Edsand, 2019). Conducting this study in Malaysia, a developing nation, adds a distinct perspective to the discourse. This alternative viewpoint from a developing country context enhances our understanding of how TIS operates in such environments.

The findings form a systematic and holistic model covering all actors—government, industry, and academia—relevant to the growth and spread of GaN technology. This model serves as a valuable tool with which the Malaysian government can identify areas in need of improvement and, in turn, facilitate the successful integration of GaN technology. Such integration would strengthen the country's overall ecosystem, talent pool, and supply chain with regard to GaN technology, making the country far more attractive for FDI and domestic direct investment (DDI). Simultaneously, this research could aid both government and private agencies in understanding how GaN technology can contribute to boosting economic and development initiatives.

6.0 Limitations and Future Works

This study was subject to several limitations. It focused exclusively on the GaN-on-GaN Program, and only stakeholders who were fully involved in the program's formation, execution, and strategy discussions were probed. Other stakeholders, such as individual researchers, were not included in the study. Therefore, other stakeholders such as researchers, suppliers, and users are recommended to include the future research. However, this meant that all participants had in-depth knowledge and could provide high-quality, informative data for this study. The results were consistent across all participants, validating the program's documentation.

While this study primarily focused on GaN development and diffusion in Malaysia with a particular emphasis on resource mobilization, it also revealed the need for further research in other functions within the TIS framework, including "knowledge development and diffusion," "influence on the direction of search," "entrepreneurial experimentation," "market formation," "legitimation," and "development of positive externalities." Its findings lay the groundwork for such future research endeavors.

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