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POROUS GAN FABRICATION: A BIBLIOMETRIC EXPLORATION OF ELECTROLESS, ELECTROCHEMICAL AND PHOTOELECTROCHEMICAL ETCHING

Syed Taufiq Akmal Syed Nasiruddin[1], Ainorkhilah Mahmood [2*], Nur Maizatul Azra Mukhtar[3], Nur Iwani Nor Izaham[4], Mahayatun Dayana Johan Ooi[5], Abdul Razak Abdul Wahab[6]

[1] Department of Applied Sciences, Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Permatang Pauh, 13500 Permatang Pauh, Penang, Malaysia.
Email:malstak06@gmail.com
[2] Department of Applied Sciences, Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Permatang Pauh, 13500 Permatang Pauh, Penang, Malaysia.
Email: ainorkhilah_sp@uitm.edu.my
[3] Faculty of Health Sciences, Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Bertam, 13200 Kepala Batas, Penang, Malaysia
Email: nurmaizatul038@uitm.edu.my
[4] Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
Email: nuriwani1999@gmail.com
[5] School of Physics, Universiti Sains Malaysia, 11800 Gelugor, Malaysia
Email: mahayatun@usm.my
[6] AiGold Engineering,13800 Butterworth, Penang, Malaysia
Email: ajaque7177@gmail.com
[*] Corresponding Author

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Abstract:

The bibliometric analysis on the topic of porous gallium nitride (GaN) was sourced from the Web of Science (WoS) Core Collection database to provide insight regarding the progression of the topic. A performance analysis and science mapping were performed using Microsoft Excel, WoS analytical tool and VOSviewer to analyze the publication of porous GaN until the year 2023. The result revealed a fluctuating trend of published documents and citations impact of porous GaN research over the past 26 years. The highest publication output of porous GaN was in the year 2016 with 20 documents while the highest yearly publication impact was in 2012 with 309 citations. Although the publication performance is fluctuating, the recent publication of porous GaN in the year 2023 is at 11 documents with four citations and is expected to rise. China ranked as the most productive country contributing to 53 documents on the topic while the USA is the most impactful country in producing quality research with 1331 overall citations. The study also included the most

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influential and prolific in terms of organizations and authors relating to the porous GaN topic. Furthermore, keyword analysis illustrated through the science mapping suggests the future trend of porous GaN involves a multidisciplinary approach concerning the fabrication of GaN through optical engineering and material characterization. Limitations of the studies included the dataset received only from the Web of Science database and not from any other source, such as Scopus or Google Scholar. The value of the study lies in providing a bibliometric understanding of the evolution, popularity, and advancement of these etching methods.

Keywords:

Bibliometric Analysis, Web of Science, VOSviewer, Porous GaN, Gallium Nitride

Introduction

The development of third-generation semiconductors such as gallium nitride (GaN) has gained attention from photonic researchers due to its unique optical and electrical properties such as wide band gap, higher breakdown voltage, and higher electron mobility compared to the previous semiconductor generation (Sharma et al., 2023; Yu, 2020). In a particular domain of GaN, introducing a nanostructure called porous GaN on the surface has enhanced the potential of innovative sensing devices (C. Zhang et al., 2018). These pores on the GaN surface create an increased surface area that enhances the material's capacity to absorb light leading to greater interaction between the semiconductor and its surrounding environment (Cui et al., 2021). Apart from the application of photodetector, the porous GaN can be utilized in chemical sensing devices for example gas sensors where the porous GaN is deposited with platinum or platinum composite to enhance the sensitivity of hydrogen gas detection (Shafa et al., 2019; Xi et al., 2019). Other applications include water splitting, light-emitting diodes, hydrogen peroxide detectors, ammonia sensing and piezoelectric (Beh et al., 2013; Jin-Ho et al., 2017; Maddaka et al., 2021; M. R. Zhang et al., 2017).

The term porous structures in the GaN semiconductor are sometimes referred to as nanoporous, microporous, or mesoporous (Cao & Xiao, 2019). Alternatively, nanostructures like nanowires, nanotowers, and nanocolumns on GaN can be technically engineered through a comparable etching process (Goswami et al., 2020; Høiaas et al., 2019; Mariana et al., 2019). The diversities of fabrication processes and conditions, including the choice of substrate contribute to the variety of nanostructures produced and their performance. For the object of the bibliometric study, the formation of porous structures through the fabrication process such as electroless etching, electrochemical etching, and photoelectrochemical etching was specified in the bibliometric study. The reason for such a specification is due to a belief among the researchers that the mentioned fabrication techniques which are categorized as wet chemical etching have quick etching duration, are more cost-effective and the setup used is simpler compared to dry etching which uses high kinetic plasma or gas to knock off the semiconductor atoms producing pores which were intricate and less economic (Al-Heuseen & Hashim, 2012). One of the backlashes of using dry etching, due to the nature of energetic ions formed in the plasma causes plasma-induced damage, poor surface morphology, and structural damage leading to minimum device performance (Pearton et al., 2000).

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The bibliometric study on porous GaN is still lacking with only one reference being found relating to the matter. In the previous study, it was shown that through the Web of Science (WoS) database, the direction of bulk GaN is moving towards the development of high voltage operation such as power electronics, power amplifiers, wide band gap semiconductors, sensors, and switches (Lam et al., 2023). The author also included in the study, the production and citation trends of GaN documents, contribution by country, source title in GaN publication and the most cited GaN publication apart from the keyword co-occurrence map. Continuing from the previous study, the present bibliometric analysis objective is to dive deeper into the topic of porous GaN, specifically exploring its viability for optoelectronic applications by wet etching fabrication technique through a comprehensive bibliometric investigation. Bibliometric analysis involves the exploration of a large volume of existing scholarly publications based on a specific topic about a study of interest to acquire the pattern of the research and the impact of research publication through performance analysis and science mapping (Donthu et al., 2021).

Literature Review

A simple design involves a brief overview of the fabrication of porous GaN using electrochemical methods or wet etching. To fabricate the porous structure the non-etched GaN is connected to the anode electrode and an inert metal such as platinum wire is connected to the cathode electrode referring to the counter electrode (Lim et al., 2018; Schwab et al., 2013). Most studies are interested in examining the effect of electrolyte used be it a base, acid, ionic liquid or organic compound on the pore formation (Heffernan et al., 2019; Wang et al., 2018). Subsequently, the investigation among researchers includes the applied potential or current source utilized to drive the electrochemical reaction, examining variations such as the choice between alternating current and direct current (Mahmood et al., 2013; Quah et al., 2016). For photoelectrochemical methods, a UV source is added to the setup illuminating the sample during the etching process. This can be suitably described as electrically enhanced photochemical etching, where the reaction is stimulated by incident light typically with energy higher than the GaN bandgap, and the role of the potential difference is solely to eliminate the photo-generated carriers (M.-R. Zhang et al., 2017). Conversely, electroless methods necessitate no external electric field to facilitate etching but depend on UV intensity to induce electron-hole formation, thereby steering the photochemical reaction (Hwang et al., 2004). Figure 1 illustrates the basic electrochemical and photoelectrochemical setup for porous nanostructure fabrication.

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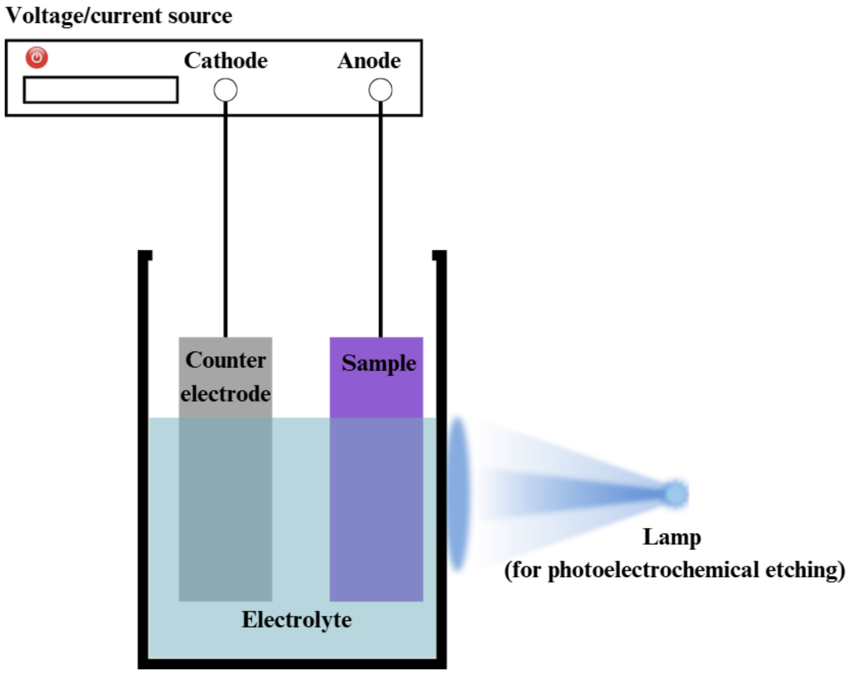

Figure 1: A Schematic Diagram of Electrochemical Etching of Porous GaN

A theorized term coined as space charge region (SCR) typically located at the semiconductor electrolyte interface (SEI) assumes a central role in the dynamics of electrochemical etching. At the SCR there are triple bonds between Ga and N atoms or dislocation that have high hole concentration defects (Hou et al., 2018). The base electrolyte also referred to as nucleophilic species, represented by an example hydroxide ion from the KOH, initiates the attack on the three bonds. This process is facilitated by an appropriate enough energy supplied through the potential difference, creating an electric field that enhances the favorability of nucleophilic attacks on the anode. Consequently, this leads to the cleavage of GaN bonds, promoting the formation of a porous nanostructure at the SEI. The electron-hole formation further facilitates the process through the UV light illumination on the sample. Thus, the redox reaction during both photoelectrochemical or photo-assisted electroless processes is similar as shown in (1).

$$2GaN + 6h^{+} \rightarrow 2Ga^{3+} + N_2 \quad (1)$$

So far and so forth, the first focus within the domain of GaN is related to the initiation of the fabrication process of bulk layer GaN on a substrate typically sapphire (Son et al., 2022). This includes considerations such as the choice of substrate, the use of a buffer layer, and the limitations of the instrument in the fabrication process (Kamler et al., 2008). Threading dislocation and defect density are influenced by the fabrication setting to grow the crystal structure (Talwar et al., 2020). Secondly, when exclusively pursuing the creation of a porous nanostructure, numerous methodologies necessitate a top-bottom approach (Cheah et al., 2015; Radzali et al., 2014). This implies that the GaN layer must be formed first before the nanostructure can be designed through the mentioned etching process. Examples of the GaN layer fabrication that are highly discussed are MOCVD and HVPE (Braniste et al., 2017). Afterward, the wet etching parameters can be investigated such as the effect of current density, electrolyte used, temperature, duration, and the presence of UV light. The generalized concerns and ambition are to gain an understanding of the factors governing the nanostructured

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formation on the semiconductor allowing for precise control of its structural development and desired optical properties. These are among the highly discussed aspects in the porous GaN areas.

Research Question

The bibliometric article aims to provide a detailed bibliometric analysis of the three major etching techniques which are electroless, electrochemical, and photoelectrochemical used in fabricating porous GaN. The analysis seeks to unveil the following aspects:

1. What is the overall publication trend of porous GaN research published from the WoS database?
2. Which country around the world exhibits the highest total publication and citation until 2023?
3. Which journals are highly cited for publishing documents within the scope of the topic?
4. Which author has the most significant WoS total publication and total citation?
5. Which document is most referred to relating to the topic?
6. What is the percentage of research funding among the published documents?
7. What are the keywords and co-occurrence patterns in the published documents on the topic of porous GaN?

Methodology

This section details the data collection and data analysis procedure. Data was acquired from the WoS Core Collection database on 26th December 2023. The data was analyzed using three tools which are WoS analytical tools (on the website), Microsoft Excel (Excel Worksheet) in format (xlsx) and VOS viewer version (1.6.19) for both performance analysis and science mapping. The first stage of the bibliometric study involves the search selection strategy where the objective of the study and topic of interest is determined. The objective and topic have been discussed in the introduction section. Subsequently from the objectives, a Boolean search term was selected that represents the topic of the study. Afterwards, the prepared Boolean search terms are used in the database where the study utilizes WoS Core Collection database for data collection. In the second stage, which is called preprocessing, the data is screened for relatedness to the study, marked on the WoS database for storage and exported into a proper data format for the analysis. Lastly, the outcome from the analysis is then presented in the results and interpretation section. Figure 2 summarizes the methodology section.

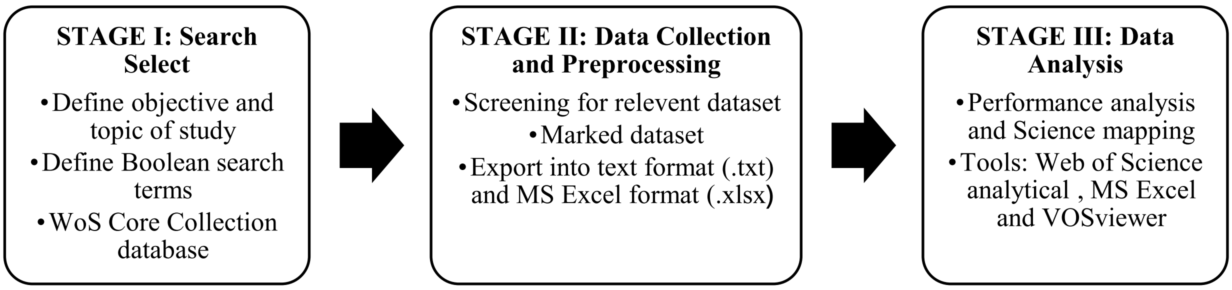

Figure 2: Flowchart of the Three-Stage Process for Bibliometric Analysis on Porous GaN

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Search Selection Strategy

WoS database was chosen due to its well-established indexing academic record that contains an enormous collection of publications of scholarly documents in a variety of fields and the likelihood of including predatory publications is minimal (Caroline Birkle et al., 2020). Thus, finding a reliable and precise collection of information for bibliometric analysis is important and the first step of the methodology is defining the search term for the topic. Including a mere "Porous GaN" term is not sufficient since the collection will generate results of non-interest criteria such as other types of semiconductors, different fabrication processes, and other nanostructures. Thus, the specific keyword is chosen in the search selection. The initial search is related to GaN and gallium nitride. Additionally, the interest of the nanostructure is on the formation of porous, mesoporous, poro* and microporous. The process of nanostructure fabrication is electrochemical, photoelectrochemical, and electroless. All the fabrication process is considered as wet etching thus the term is added.

Figure 3 displays the Venn diagram representing the explained terms to be used in the WoS search. The box of WoS database contains all the existing datasets recorded or set universe. Set A contains nanostructure terms such as "porous", "nanoporous", "mesoporous", "poro*" and "microporous". Set B contains the name of the semiconductor of study for example "GaN" and "Gallium nitride". While set C contains the fabrication process which is "electrochemical", "photoelectrochemical", "electroless", and "wet etching". The intercept of all the sets produces the desired set of the data collection which is called set D. As such, the desired term reflects the area of the chosen Boolean search term. In which the set D represented the overlapping of A, B, and C. The set notation of D can be represented as $D = A \cap B \cap C$. Thus, the intercept of D is considered as the close representation of the interested Boolean search term. Therefore, by referring to Table 1 the Boolean search term is created for the search that highly reflects the topic of the study with its selected fabrication processes, limited to only porous nanostructure and GaN semiconductor. The search type for the WoS database was set to topic search.

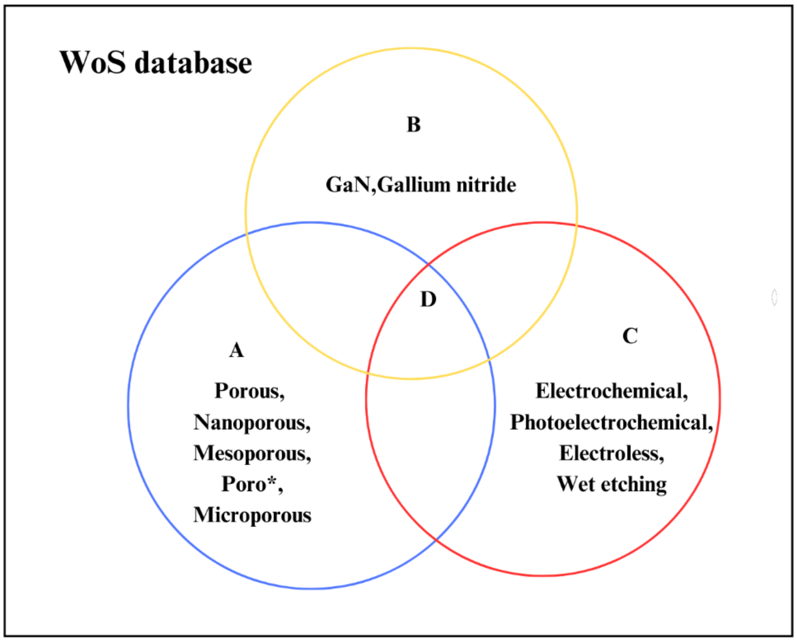

Figure 3: Venn Diagram for a Better Overview of the Selected Boolean Search Term

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Table 1: Search Inquiries in Web of Science

Topic	Porous GaN
Boolean search term	(Porous OR nanoporous OR mesoporous OR Poro* OR microporous) AND ("GaN" OR "gallium nitride") AND (electrochemical OR photoelectrochemical OR Electroless OR "wet etching") (Topic)
Countries/ Region	All
Timespan	All
Document types	All types
Indexes	Science Citation Index Expanded (SCI-EXPANDED), Conference Proceedings Citation Index – Science (CPCI-S) and Emerging Sources Citation Index (ESCI)

Data Collection and Preprocessing

In Figure 4, the results of the search inquiries yielded a total of 345 outputs, with 156 records subsequently excluded due to their unrelated content to the study consequently falling outside the scope of this study. Not only does the content of the data collection contain duplication but includes other semiconductors such as InGaN, and porous silicon which is similarly fabricated with the same wet etching. These records are removed to highly specify the porous GaN fabrication on the three major etching methods. The search inquiries were intentionally not filtered by specific countries or limited to particular regions as to provide a broad scope for comprehensive analysis of the topic. Meanwhile, the timeframe for the study spanned all years. Thus, the final dataset acquired from the database comprised 189 entries that highly reflect the topic. The existing citation indexes within these datasets were from the Science Citation Index Expanded (SCI-EXPANDED), Conference Proceedings Citation Index – Science (CPCI-S) and Emerging Sources Citation Index (ESCI). The detailed search inquiries are outlined in Table 1. In essence, the data collection process adhered to the guidelines outlined in the Preferred Reporting Items of Systematic Reviews and Meta-Analysis (PRISMA).

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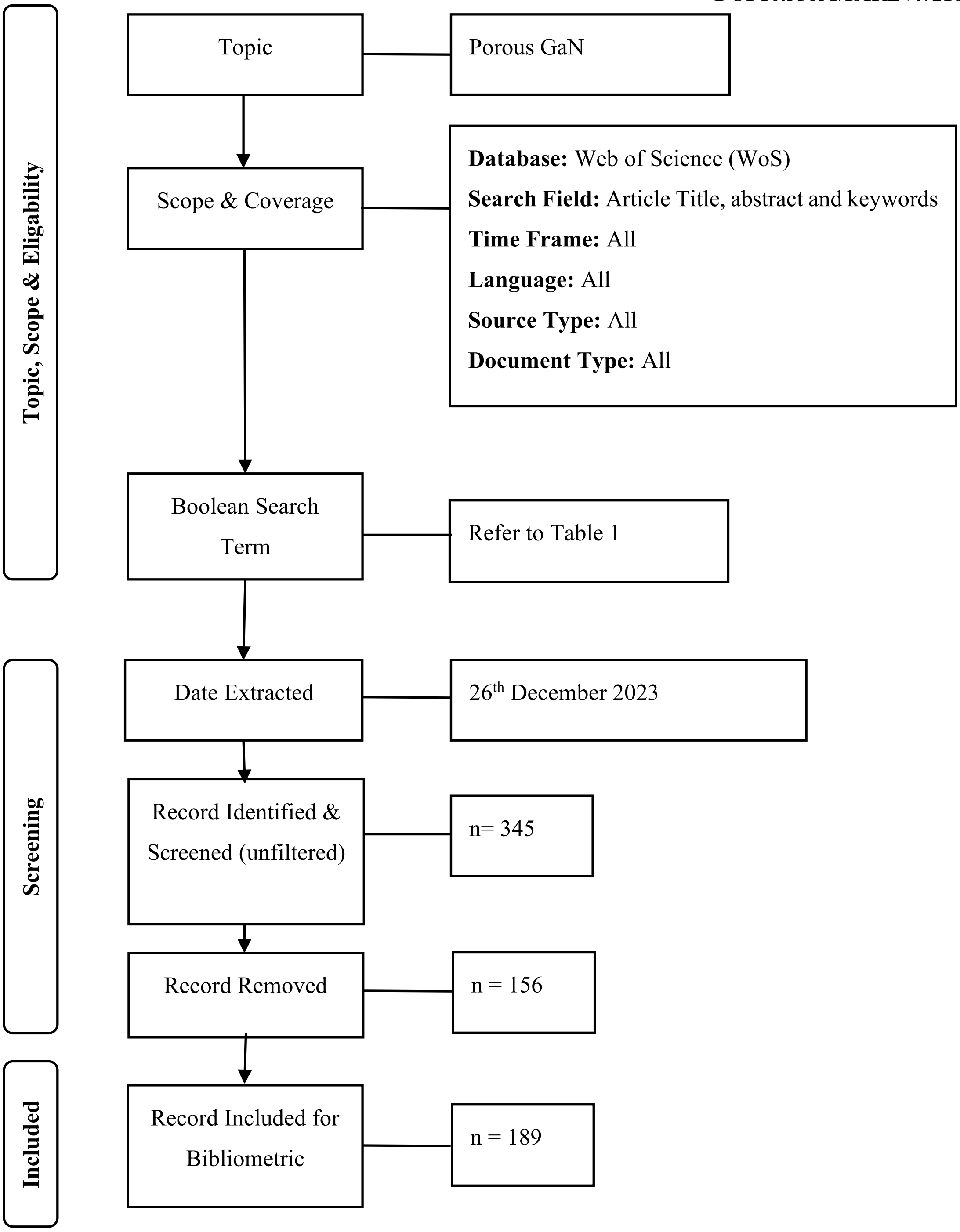

Figure 4: PRISMA Flow Diagram

Data Analysis

The dataset obtained from WoS Core Collection was analyzed using two categories of bibliometric analysis which are performance analysis and science mapping. In performance analysis, measurements such as authors, organization, country, year of publication, source title, total citation, research area, WoS categories, and funding information are analyzed. Some additional variables such as citation per document, % funded publication and citation per year were added to derive additional information based on the collected base data in MS Excel. It was known that, apart from MS Excel and WoS analytic tools, VOSviewer can be used to

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perform performance analysis. The result conveyed from VOSviewer can be seen through citation analysis of influential and prolific measurements of both organizations, source titles, and authors. Influential measurement refers to the number of citations an author, organization, or source title receives while prolific refers to the number of documents published by the author, organization, or source title. Meanwhile, WoS analytics tools were used to analyze research areas and WoS categories. Without being said, MS Excel on the other hand was used to analyze general performance analysis such as the publication performance of the countries, year of publications, and funding information. The use of MS Excel also facilitates the analysis done on VOSviewer.

Results and Discussion

A thorough examination of extracted data from the WoS database was performed. The information obtained on 26th December 2023 from processing and analysis of the data includes a total of 189 documents with three document types consisting of research articles, reviews, and proceedings papers. The language used is mainly English in all the extracted documents. The existing research area covers a varied range of studies, spanning 13 distinct research areas. There are 23 categories within the WoS classification system. A total of 537 authors are actively engaged in the exploration of porous GaN. Out of the 189 published documents, 120 have received funding from their respective organization, contributing to an overall citation count of 3077. Table 2 shows the summary of the information gathered from the analysis of the porous GaN topic.

Table 2: Summary of Information from the Porous GaN Search Inquiry

Item	Productivity
Total documents	189
Document types	3
Language	1
Research area	13
WoS category	23
Involved countries	27
Authors	537
Funded publication	120
Total overall citations	3077

Publication Performance in Porous GaN Research and Documents Type

From Table 3, only 27 countries existed in the WoS database from the year 2000 to 2023 as of 26th December 2023. The countries are Belgium, China, England, Finland, France, Germany, Greece, India, Iraq, Ireland and Netherlands, Japan, Jordan, Malaysia, Moldova, Norway, Poland, Portugal, Romania, Russia, Saudi Arabia, Singapore, South Korea, Switzerland, Taiwan, United Arab Emirates and United State (USA). The total publication on the topic accounts for 189 documents with an accumulated citation of 3077 citations. The average citation per document is 13.9. From the analysis, China, USA, and Malaysia highly contribute to the porous GaN publication which are 53, 39, and 38 documents respectively. The highest impact among the publications is from the USA with an overwhelming 1331 citations exceeding China and Malaysia with only 709 and 439 citations respectively. In terms of citations per document, Belgium surpasses the USA with 63.0 citations per document, although having only one publication. Meanwhile, the USA stands as the second highest with 34.1 citations per document, reflecting a total of 39 published documents.

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Table 3: Publications Performance of Countries Contributing to the Porous GaN Research

Country	Documents	Citations	Citation per Document
China	53	709	13.4
USA	39	1331	34.1
Malaysia	38	439	11.6
South Korea	24	430	17.9
Singapore	12	283	23.6
Japan	10	123	12.3
Taiwan	9	180	20.0
Moldova	5	52	10.4
Saudi Arabia	5	48	9.6
England	4	109	27.3
Russia	4	56	14.0
France	3	55	18.3
India	3	37	12.3
Portugal	3	19	6.3
Iraq	3	16	5.3
Jordan	2	21	10.5
Switzerland	2	19	9.5
Finland	2	8	4.0
Poland	2	0	0.0
Belgium	1	63	63.0
Norway	1	19	19.0
Greece	1	9	9.0
United Arab Emirates	1	8	8.0
Germany	1	6	6.0
Romania	1	6	6.0
Ireland	1	2	2.0
Netherlands	1	2	2.0

Based on Figure 5 out of the 189 publications, the main document type is research articles, constituting 87.8% of the total with 166 documents. 10.1% of the publications represent the proceedings paper with 19 documents recorded. The smallest fraction of document types is the review paper which constitutes 2.1% with only four documents recorded in the WoS database. The high percentage of articles suggests that the porous GaN topics tend to favor research articles compared to other document types. This underscores the lack of review articles on the topic of porous GaN in comparison to other types of documents. Additionally, the supporting aspect of the article having to undergo rigorous peer review confirming the high research quality and laborious manuscript preparation obeying to the journal guidelines compared to proceeding papers that are less stringency and less structurally adhere to publisher guidelines (Madhuri S Kurdi, 2015). Nonetheless, the quality of proceeding papers is guaranteed as it has been presented and discussed with other participants at the conferences.

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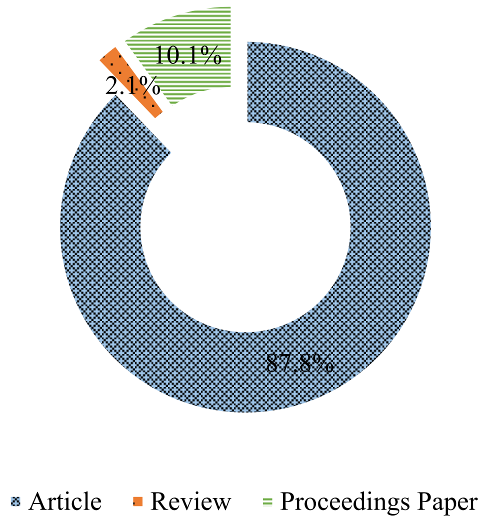

Figure 5: Percentage of Document Types on Porous GaN Publication

Figure 6 shows the document and citation performance of the published porous GaN research from WoS database. From the figure, the first emergence of porous GaN publication was in the year 1997 with a single document from Russian authors named Mynbaeva et al. titled "Porous GaN" (Mynbaeva & Tsvetkov, 1997). The study highlights the anodization process of GaN in electrochemical cell under UV illumination producing porous nanostructure. The paper received four citations as of 26^{th} December 2023. The second paper was published in 1998 by group of Japanese scholars named Hashimoto et al. The publication titled "Formation of GaN nano-column structure by nitridation" received 17 citations as of the current date of the study (Hashimoto et al., 1998). The article focuses on the formation of nano-columns using electrochemical anodization coupled with thermal nitridation technique to fabricate the GaN from GaAs under specified conditions. It was known back then GaAs can be easily converted into GaN by the thermal nitridation technique to produce low dimensional nano-structure column. Meanwhile, there is an absence of publication in the years 1999, 2000, and 2001 regarding the topic of porous GaN from the WoS database. However, there is proof of publication regarding the topic of porous GaN present in that year on another database such as Google Scholar (Huygens et al., 2000). This showcases that the performance of porous GaN publication is communicated through local indexing journals. Nonetheless, the non-existence of publication in that year will not be discussed as that is due to the limitation of the study. The overall result of the publication trend of porous GaN topic from the year 1997 to 2023 (27 years) indicated increases over time with fluctuations in yearly document outputs and citation count. The fluctuations might result in the semiconductor industry's dynamic and its changing interest in the third generation of semiconductor material under study (Deng, 2022). The peak publication output was in 2016 with 20 documents while the citation of the same year was 230 citations. The highest yearly citation accumulated 309 citations in 2012 with 13 accumulated documents. Despite the fluctuation, there is still ongoing research on porous GaN in the last two decades since 2002 with the latest in 2023 there have been 11 documents published on the topic with decreasing citation count to four.

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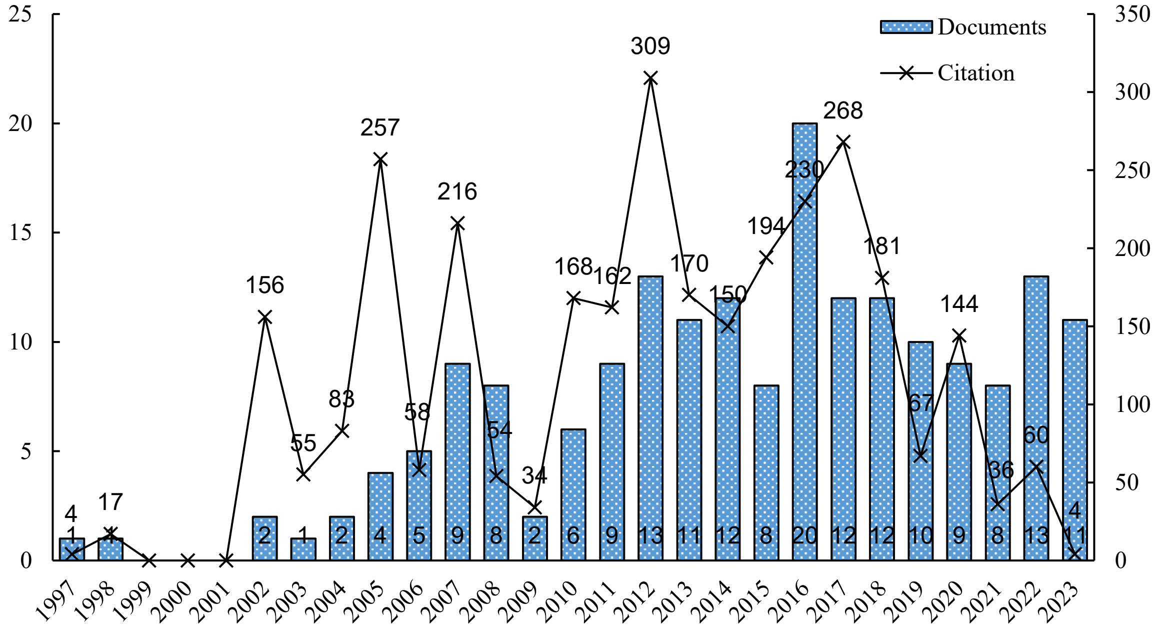

Figure 6: Document and Citation Trend of Porous GaN Publications

Research Area and Type of WoS Category

Based on WoS website, the difference between the research area and type of WoS category is that the first refers to the subject categorization scheme that is shared by all Web of Science product databases while the latter categorization labelled at the journal level. Both highly reflect one another and can be considered as a representation of the acquired dataset topic of study without much ambiguity. Thus, the discussion on the acquired frequency will not be a major concern. The analysis of the data is gathered from the WoS on website analytics tools. The data from the website can be analyzed through tables or charts. From Table 4, the frequently mentioned research areas are "Material Science" and "Physics" with the frequency of 111 and 101 respectively. This shows the entirety of the porous GaN semiconductor is in the domain of material science and physics.

Table 4: Research Area of Porous GaN Publications

Research Areas	Frequency	% (N = 189)
Materials Science	111	58.73
Physics	101	53.439
Science Technology Other Topics	38	20.106
Chemistry	36	19.048
Electrochemistry	27	14.286
Engineering	22	11.64
Optics	19	10.053
Metallurgy Metallurgical Engineering	8	4.233
Crystallography	3	1.587
Energy Fuels	3	1.587
Instruments Instrumentation	3	1.587

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Remote Sensing	1	0.529
Spectroscopy	1	0.529

Meanwhile, in Figure 7, the most frequently mentioned WoS category is similar to the research area label which is "Materials Science Multidisciplinary" and "Physics Applied" with a frequency of 87 and 80 respectively. However, the WoS category has wider labeling of scientific domain, here in the example the WoS category has 23 different domain labels compared to research area which only contains 13 area labels. Furthermore, despite both the research area and WoS category having similar least mentioned label such as "Remote Sensing" and "Spectroscopy", WoS category has two additional labels which is "Engineering Multidisciplinary" and "Materials Science Ceramics". This shows the labeling of WoS category is more specific to the journal level scope and subject of study.

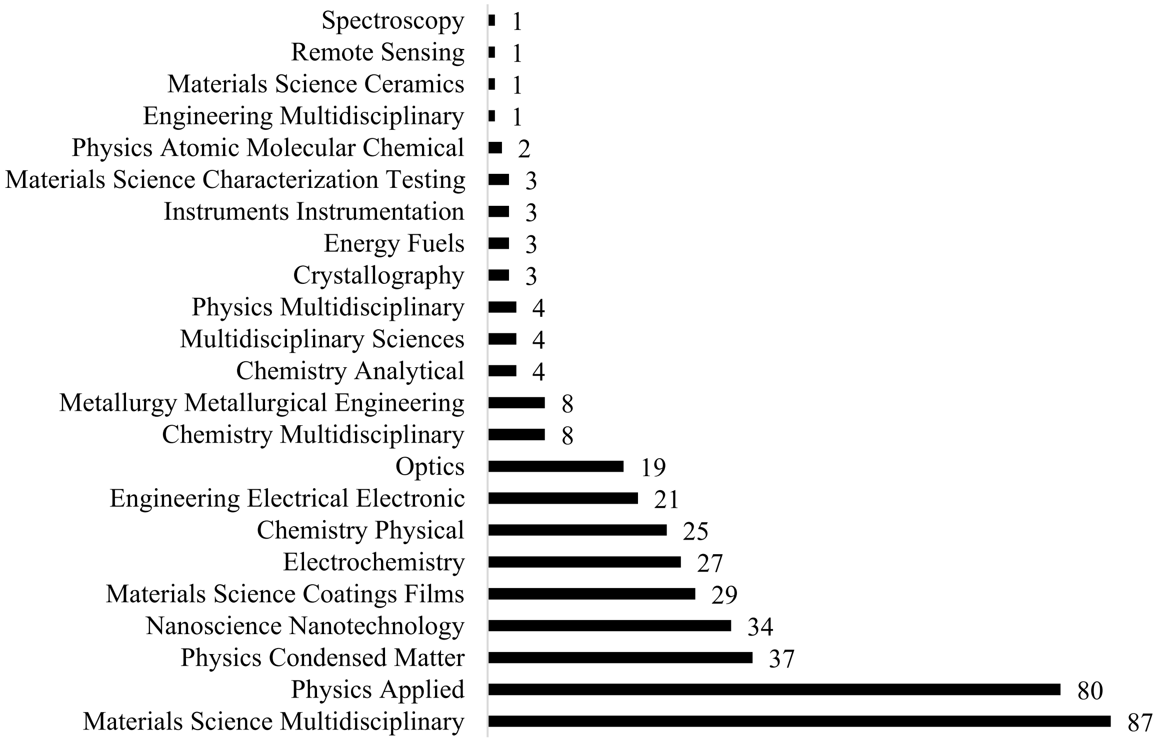

Figure 7: WoS Category of Porous GaN Publication.

Influential and Prolific Organizations

In Table 5, the most influential organization that has the highest citation count is Yale University from USA with a total of 544 citation counts. Following closely is Universiti Sains Malaysia with 439 citation counts. Among the countries that listed in the top 10 influential organizations, there are three from USA, one from Malaysia, two from China, one from South Korea, two from Singapore, and one from Taiwan. All the listed countries are actively impacting the landscape of porous GaN research. Meanwhile, Table 6 shows the prolific organization that produced a number of documents pertaining to the topic of porous GaN research. The most prolific organization that has produce the highest publication output throughout the period of study is Universiti Sains Malaysia with 38 published documents following Shandong University a China organization with 23 documents. However, it should

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be noted that China has the most accumulated documents published overall with 53 documents. This means that other organizations in China have contributed to the publication separately. Despite Malaysia having 38 overall publications as seen in Table 3, this shows the collaboration among countrymen of different local organizations in producing publications. This is not only limited to Malaysia but other nations too. As such, the publication of a single paper consisting of multiple authors of different organizations is counted as one despite having a similar nationality. And if the co-authorship of the publication consists of individuals of different nationalities, then a count of one is added to that country label separately resulting in an increasing number of counts to each nation existing in a single publication. This gives rise to Table 6. The similarity is true with Table 5. Although this is a highly technical statistical analysis clarification, the numbering result gathered from the analysis should not be a matter of discussion since the result is derived from VOSviewer with an accompanied thesaurus file that reduces the repetition of similarly named organizations. The country that is listed in the top 10 prolific organization, there are two from Malaysia, two from China, three from the USA, two from Singapore, one from South Korea, and one from Japan.

Table 5: Top 10 Influential Organizations in Porous GaN Research

Rank	Influential Organization	Country	Citation
1	Yale University	USA	544
2	Universiti Sains Malaysia	Malaysia	439
3	Massachusetts Institute of Technology	USA	434
4	University of Illinois	USA	370
5	Shandong University	China	297
6	Chonnam National University	South Korea	289
7	Agency for Science, Technology and Research	Singapore	283
8	National University of Singapore	Singapore	253
9	Chinese Academy of Sciences	China	250
10	National Chung Hsing University	Taiwan	137

Table 6: Top 10 Prolific Organizations in Porous GaN Research

Rank	Prolific Organization	Country	Documents
1	Universiti Sains Malaysia	Malaysia	38
2	Shandong University	China	23
3	Yale University	USA	14
4	Chinese Academy of Sciences	China	13
5	Agency for Science, Technology and Research	Singapore	12
6	Chonnam National University	South Korea	11
7	Massachusetts Institute of Technology	USA	11
8	Universiti Teknologi MARA	Malaysia	10
9	National University of Singapore	Singapore	9
10	Hokkaido University	Japan	7
10	University of Illinois	USA	7

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Influential and Prolific Source Title

There are 96 source titles that have been published in WoS core collection related to porous GaN. Table 7 and Table 8 rank the influential and prolific source titles based on citations and documents published respectively. The journal impact factor (JIF) is a widely used metric to calculate the significance of a journal (Mohit Sharma et al., 2014). JIF is calculated by Clarivate and shows the yearly average number of citations of papers published in the previous two years in the journal journals with higher impact factors generally perceived as more influential than those with lower ones. The metric used to rank the source title is based on the citation of the published document in the journal. From Table 7 and Table 8, the highest cited source title is "*Applied Physics Letters*" with 382 accumulated citations and among the journal that has been chosen to be published the second most among the porous GaN researchers with a total of 11 document publications. From the website of the source title, the journal covers important topics in the applied physics domain including photonics and optoelectronics as one of the tops mainly discussed interests. In the meantime, the most prolific source title with abundant document publications as seen in Table 8 is "*Journal of the Electrochemical Society*" with 13 documents in total and 137 citations (rank 8 in the influential source title), making the source title the most publication published in porous GaN research. This journal mostly discusses electrochemistry and solid-state science pertaining to the electrochemical engineering of nanostructure and photonic devices that agree on the topic of porous GaN.

Table 7: Influential Source Title in Porous GaN Publications

Rank	Source Title	Publisher	Country	Citations	JIF (2022)
1	*Applied Physics Letters*	AIP Publishing	USA	382	4.0
2	*Journal of Applied Physics*	AIP Publishing	USA	204	3.2
3	*Applied Surface Science*	Elsevier	Netherlands	171	6.7
4	*Journal Of Physical Chemistry C*	American Chemical Society	USA	158	3.7
5	*ACS Photonics*	American Chemical Society	USA	150	7.0
6	*Thin Solid Films*	Elsevier Science SA	Netherlands	148	2.1
7	*Journal of the Electrochemical Society*	The Electrochemical Society	USA	137	3.9
8	*Materials Letters*	Elsevier	Netherlands	129	3.0
9	*ACS Applied Materials & Interfaces*	American Chemical Society	USA	120	9.5
10	*Sensors and Actuators B-Chemical*	Elsevier Science SA	Switzerland	120	8.4

Table 8: Prolific Source Title in Porous GaN Publications

Rank	Source Title	Publisher	Country	Documents	JIF (2022)
1	*Journal of the Electrochemical Society*	The Electrochemical Society	USA	13	3.9
2	*Applied Physics Letters*	AIP Publishing	USA	11	4.0
3	*Materials Letters*	Elsevier	Netherlands	11	3.0
4	*Applied Surface Science*	Elsevier	Netherlands	8	6.7

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5	*ACS Applied Materials & Interfaces*	American Chemical Society	USA	7	9.5
6	*Journal of Alloys and Compounds*	Elsevier Science SA	Switzerland	6	6.2
7	*Thin Solid Films*	Elsevier Science SA	Netherlands	6	2.1
8	*Journal of Applied Physics*	American Institute of Physics	USA	5	3.2
9	*Semiconductor Science and Technology*	IOP Publishing LTD	England	5	1.9
10	*ECS Journal of Solid-State Science And Technology*	The Electrochemical Society	USA	4	2.2

Authorship

The authorship section plays an important role in determining the names of the scholars who are considered experts in the field of porous GaN research. As such, the citation and document published by the researchers are proof of the contribution to the development of the field through manuscript writing that verily requires laborious work (Shubha & Bhupinder, 2021).This will provide the reader with potential collaboration opportunities regarding the topic of interest should it offer the attention. In Table 9, the most influential author contributing to the highest impact of porous GaN research is “Han, Jung” from the USA and affiliated with Yale University. The author also published a total of 14 documents related to the topic of porous GaN as seen in Table 10. Next, the most prolific author producing the most investigation on the porous GaN topic is “Hassan, Zainuriah” from Malaysia. The Author is affiliated with Universiti Sains Malaysia with a total of 31 documents and a total of 330 citations (see Table 10).

Table 9: Influential Authors in Porous GaN Research

Rank	Influential Author	Country	Affiliation	Citations
1	Han, Jung	USA	Yale University	544
2	Bohn, Paul W.	USA	University of Notre Dame	429
3	Hassan, Zainuriah	Malaysia	Universiti Sains Malaysia	330
4	Ryu, Sang-Wan	South Korea	Chonnam National University	289
5	Chua, Soo Jin	Singapore	Agency for Science, Technology and Research	283
6	Chen, Danti	USA	Yale University	278
7	Williamson, Todd	USA	University Illinois	268
8	Xiao, Hongdi	China	Shandong University	259
9	Fitzgerald, Eugene A.	USA	Massachusetts Institute of Technology	242
10	Fong Kwong, Yam	Malaysia	Universiti Sains Malaysia	232

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Table 10: Prolific Authors in Porous GaN Research

Rank	Prolific Author	Country	Affiliation	Documents
1	Hassan, Zainuriah	Malaysia	Universiti Sains Malaysia	31
2	Xiao, Hongdi	China	Shandong University	19
3	Fong Kwong, Yam	Malaysia	Universiti Sains Malaysia	19
4	Han, Jung	USA	Yale University	14
5	Chua, Soo Jin	Singapore	Agency for Science, Technology and Research	12
6	Ryu, Sang-Wan	South Korea	Chonnam National University	11
7	Bohn, Paul W.	USA	University of Notre Dame	10
8	Yang, Xiaokun	China	Shandong University	10
9	Ma, Jin	China	Shandong University	9
10	Cao, Dezhong	China	Xi'an Polytechnic University	9

Most cited and Popular Publications

The most cited publication refers to the highest accumulation of citations a document has while the popular publication refers to the highest average of citations per year from the published date until the year 2023. The information revealed in this section shares the important document that highly reflects the topic of porous GaN research and its usefulness as a reference for the audience embarking on the topic. The affiliations in the table describe the affiliations of the main author and the year indicates the year of the publication. In Table 11, the most cited publications in porous GaN study are titled "Mesoporous GaN for Photonic Engineering-Highly Reflective GaN Mirrors as an Example" authored by Zhang et al. from Yale University (USA) with 116 accumulated citations. The publication is considered well-cited and among the latest relative to other publication titles of the category since its published year is in the year 2015.

Table 11: Top 10 Most Cited Porous GaN Publications

Rank	Authors	Title	Affiliations	Main Author Country	Year	Citation
1	Zhang et al.	Mesoporous GaN for Photonic Engineering-Highly Reflective GaN Mirrors as an Example	Yale University	USA	2015	116
2	Chen et al.	Nanopores in GaN by electrochemical anodization in hydrofluoric acid: Formation and Mechanism	Yale University	USA	2012	108
3	Li et al.	In-plane Bandgap Control in Porous GaN Through Electroless Wet Chemical Etching	University of Illinois System	USA	2002	102
4	Vajpeyi et al.	Investigation of Optical Properties of Nanoporous GaN Films	National University	Singapore	2005	84

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			of Singapore			
5	Zhang et al.	A Conductivity-Based Selective Etching for Next Generation GaN Devices	Yale University	USA	2010	83
6	Williamson et al.	Porous GaN as a Template to Produce Surface-Enhanced Raman Scattering-Active Surfaces	University of Illinois System	USA	2005	78
7	Tseng et al.	Anodic Etching of n-GaN Epilayer into Porous GaN and Its Photoelectrochemical Properties	IMEC	Belgium	2014	63
8	Vajpeyi et al.	High Optical Quality Nanoporous GaN Prepared by Photoelectrochemical Etching	National University of Singapore	Singapore	2005	56
9	Díaz et al.	Morphology Evolution and Luminescence Properties of Porous GaN Generated via Pt-Assisted Electroless Etching of Hydride Vapor Phase Epitaxy GaN on Sapphire	University of Illinois	USA	2003	55
10	Díaz et al.	Morphology and Luminescence of Porous GaN Generated via Pt-Assisted Electroless Etching	University of Illinois	USA	2002	54

Next in Table 12, the most popular porous GaN publication is “Synthesis Gallium Nitride on Porous Silicon Nano-Structure for Optoelectronics Devices” by Jabbar et al. from the University of Technology (Iraq) with 15 citations per year. Although its recently released in 2022, the publication has already amassed a substantial number of citations per year, this shows its immediate influence and recognition in the scholarly community. Similar in Table 11, the publication titled “Mesoporous GaN for Photonic Engineering-Highly Reflective GaN Mirrors as an Example” is the second most popular publication in Table 12 and among the well-cited documents by the researcher throughout its eight years of publication.

Table 12: Top 10 Most Popular Porous GaN Publications

Rank	Author	Title	Affiliations	Main Author Country	Citation	Year	Citation per Year
1	Jabbar et al.	Synthesis Gallium Nitride on Porous Silicon Nano-Structure for Optoelectronics Devices	University of Technology	Iraq	15	2022	15.00
2	Zhang et al.	Mesoporous GaN for Photonic Engineering-Highly Reflective GaN Mirrors as an Example	Yale University	USA	116	2015	14.50
3	Guo et al.	A Porous GaN/MoO3 Heterojunction for Filter-Free, Ultra-Narrowband Ultraviolet Photodetection	Wuyi University	China	11	2022	11.00
4	Yang et al.	Light Modulation and Water Splitting Enhancement Using a Composite Porous GaN Structure	Chinese Academy of Sciences	China	53	2018	10.60
5	Griffin & Oliver	Porous Nitride Semiconductors Reviewed	University of Cambridge	England	30	2020	10.00
6	Shushanian et al.	Analysis of the n-GaN Electrochemical Etching Process and its Mechanism in Oxalic Acid	King Abdullah University of Science & Technology	Saudi Arabia	10	2022	10.00
7	Chen et al.	Nanopores in GaN by Electrochemical Anodization in Hydrofluoric Acid: Formation and Mechanism	Yale University	USA	108	2012	9.82
8	Zhang et al.	Electrosynthesis of Gold Nanoparticles/Porous GaN Electrode for Non-Enzymatic	Chinese Academy of Sciences	China	53	2017	8.83

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		Hydrogen Peroxide Detection					
9	Lheureux et al,	Tamm Plasmons in Metal/Nanoporous GaN Distributed Bragg Reflector Cavities for Active and Passive Optoelectronics	University of California System	USA	26	2020	8.67
10	Monaico et al.	Porous Semiconductor Compounds	Technical University Moldova	Moldova	25	2020	8.33

Keywords Analysis

This study's selected type of analysis is co-occurrence analysis in VOSviewer, which exclusively utilizes author keywords. Author keywords through co-occurrence are used to identify the core information that reflects the main content of the articles. This choice was made primarily due to its ability to provide a more streamlined and focused examination of the bibliometric data, aligning with the study's emphasis on author selections, as opposed to Keyword Plus, which tends to be broader in scope (J. Zhang et al., 2016). The node and label in the mapping represent the occurrence of a keyword, its size represents the frequency of occurrence while the colors represent the cluster as seen in Figure 8. Meanwhile, the overlay visualization’s color in Figure 9 indicates the year of the author keyword occurrence. Additionally, the distance between the nodes indicates the degree of relatability in the keyword. The higher the occurrence of an author keyword the bigger the node appeared in the mapping. All the author keywords in Figure 8 and Figure 9 have a minimum of two frequencies of occurrence. The keywords analysis reveals the 57 author keywords with each being included in the six colored clusters, which are red, green, blue, yellow, purple, and cyan. The red cluster consists of 20 author keywords such as corrosion, electrical properties, electroless deposition, electrolyte, GaN, H_2O_2 detection, hydrogen sensor, ionic liquid, luminescence, nanoparticles, optical materials and properties, photo-electrochemical etching, photoelectrochemical water splitting, porosity, porous gallium nitride, porous materials, Schottky barrier height, semiconductor and structural. This cluster seems to relate between the physical alteration of the porous GaN and the effect it produces in the electrical and optical properties of the material. The second cluster, colored in green has 13 author keywords which are Bragg reflectors, DBR, electrochemical etching, high index contrast, laser diode, lift-off, light-emitting diodes, modal gain, MQW structure, nanoporous, optical engineering, refractive index and regrowth. This cluster reflects the porous GaN interest among authors in its optoelectronic application. Next, the cluster in blue contains 12 author keywords which are annealing, anodic etching, electrochemistry, electrodeposition, etching, GaN-based DBR, iii-iv semiconductor, nanostructures, photonics, sensors, solar water splitting, and wet etching. The keywords in this cluster suggest various aspects of GaN including its fabrication, optical application, and its application in sensor and solar technology. The yellow cluster contains eight author keywords which are metal-semiconductor-metal (MSM) photodiode, PL, porous GaN, Raman spectroscopy and photoluminescence, RF-MBE, scanning electron microscope, SEM, and XRD. This cluster represents the type of analysis done on the porous GaN to obtain its characteristics. The purple cluster has three author keywords which are heterostructure, high sensitivity, and photodetector performance. This cluster suggests a focus on a specific type of

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semiconductor structure for example a heterostructure, considered to exhibit high sensitivity in the context of photodetectors. And finally, the cyan color cluster contains a single author keyword which is water splitting. This keyword refers to the photocatalyzed separation of water into its constituent elements.

For a closer inspection of author keyword occurrence, Table 14 shows the top 20 of author keyword terms with their frequency of occurrence. The highest occurrence of the author keywords is porous GaN at 50 occurrences. The author keywords also mention the most used fabrication process of porous GaN which are electrochemical etching and photoelectrochemical etching both mentioned 31 and 18 times throughout the bibliometric analysis. The author keywords "Raman spectroscopy and photoluminescence" and photodetector performance convey the combined characterization of both the structural and optical properties to detect light. Both keywords are among the highly mentioned author keywords at 21 and 12 frequencies of occurrence.

Looking at the overlay visualization of the map in Figure 9, the newly emerging trend relating to porous GaN indicated by color yellow are high index contract, optical engineering, scanning electron microscopy (SEM), GaN-Based DBR, refractive index, sensors, photonics, etching, wet etching, high sensitivity, photonics, and etching. This evolving trend suggests the multidisciplinary approach involving the application of porous GaN in distributed Braggs reflectors in sensor development through optical engineering and material characterization that can be achieved through the fabrication of porous structures in GaN.

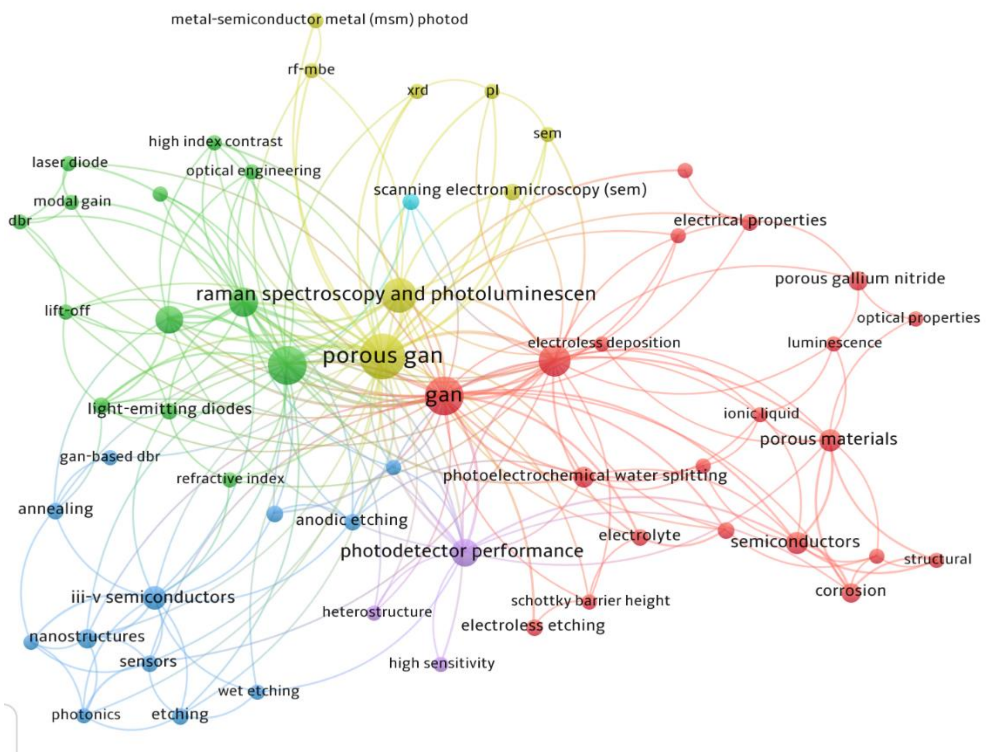

Figure 8: Network Visualization of Co-Occurrence Map

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Table 14: Top 20 Author Keywords

Author Keyword	Occurrences	Total link Strength
porous GaN	50	99
GaN	30	73
electrochemical etching	31	68
Raman spectroscopy and photoluminescence	21	48
photo-electrochemical etching	18	44
nanoporous	13	34
photodetector performance	12	30
bragg reflectors	12	29
porous materials	6	17
semiconductors	6	17
iii-v semiconductors	7	16
corrosion	4	12
photoelectrochemical water splitting	5	12
regrowth	3	12
light-emitting diodes	3	11
electrolyte	3	9
sensors	3	9
anodic etching	3	8
high index contrast	2	8
nanostructures	4	8

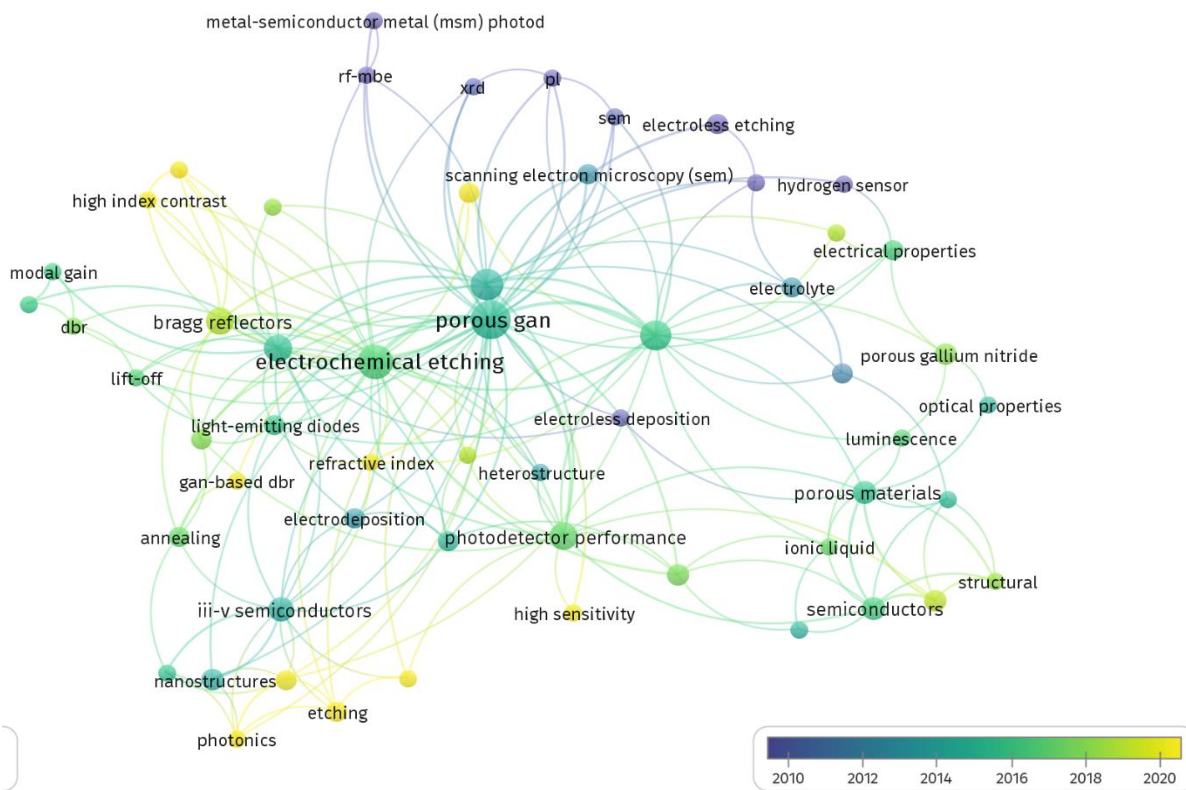

Figure 9: Overlay Visualization Map of Co-occurrence Consisting of Year Indicator.

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Conclusion

The study on porous GaN research topic was acquired from a recognized database, WoS Core Collection, and has been analyzed bibliometrically on criteria such as the publication trend of the topic, performance of the countries involved, related source title, renowned author, well-known publication, funding information and the co-occurrence pattern among the published documents. The dataset acquired has no range of years except until the 26th of December 2023. The first emergence of the porous GaN topic in WoS was published in 1997 with a title "Porous GaN" by Mynbaeva et al. (Mynbaeva & Tsvetkov, 1997). The highest publication of porous GaN was in the year 2016 with 20 documents while the highest yearly citation was in 2012 with 309 citations. Despite the fluctuation in the porous GaN publication output and impact, the topic is still relevant with 11 documents published and a total citation of four in 2023. The citation is expected to increase in the next year since the citation in 2022 is 60. The country that produces the highest document on the topic is China with 53 total publications while the USA has the most impactful publication with 1331 citations. The most influential source title is "Applied Physics Letters" by AIP Publishing with a 382 total citations and a 4.0 impact factor (2022). The most prolific source title is "Journal of the Electrochemical Society" by The Electrochemical Society with 13 publications and a 3.9 impact factor (2022). The core author with impactful publication is "Han, Jung" from Yale University, USA with 544 total citations and the most productive author with the highest publication output is "Hassan, Zainuriah" from Universiti Sains Malaysia, Malaysia with 31 total publications. The most preferred document relating to the porous GaN topic is "Mesoporous GaN for Photonic Engineering-Highly Reflective GaN Mirrors as an Example" by Zhang et al. from Yale University, USA which has been accumulating citations 116 since the year 2015. Thus, making the article significant in the porous GaN research. A notable mention regarding the research funding, 96% of China's publications have been funded comparable to its large publication output at a total of 50 documents published. In the keyword analysis, it was found that the newly emerging trend of porous GaN publication is focusing on a multidisciplinary approach involving the application of GaN in distributed Braggs reflectors in sensor development through optical engineering and material characterization that can be achieved through the fabrication of porous structures in GaN.

Lastly, analysis is not without its limitations. Firstly, the study uses Boolean search term to limit the acquisition of datasets from the WoS database, and manual removal or unrelated documents is done. During the data collection and preprocessing, it was recognized that the WoS topic search included a low accuracy of search output. There have been detected topics that do not regard the porous GaN, such as the inclusion of other types of semiconductors, InGaN, InN, and SiC using a similar fabrication process. Some also included the usage of GaN as substrate, however the porous structure was formed on different semiconductor types. Next, the search criteria also involved the electrochemical properties of unrelated semiconductors, but the study interest is on the electrochemical fabrication of GaN to create a porous nanostructure. Finally, most of the search output produced by WoS does not entirely reflect the Boolean search inquiries where terms such as electrochemical and porous defined in the study only act as minor words in the topic search, and not all the logic AND terms such as GaN are included. Thus, the provided Boolean search does not necessarily produce dataset output as expected. Consequently, irrelevant documents have been removed manually to improve the accuracy of the analysis despite it being believed some related topic might be missed from data collection as can be seen in the year 1999-2001 where no record of porous GaN was found.

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