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An Informetric View to the Negative Capacitance Phenomenon at Interlayered Metal-Semiconductor Structures and Distinct Electronic Devices

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Keywords

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Abstract

Negative Capacitance (NC) phenomenon, which can be explained as the material exhibiting an inductive behavior, is often referred to as "anomalous" or "abnormal" in the literature. Especially in the forward bias/deposition region, the presence of surface states (Nss) and their relaxation times (τ), series resistance (Rs), minority carrier injection, interface charge loss in occupied states under the Fermi energy level, parasitic inductance, or poor measuring equipment calibration problems can be counted among the causes of this phenomenon. Studies on NC behavior have shown that this behavior can be observed for different frequencies, temperatures, and related parameters at forward biases. However, the NC behavior, which appears as an unidentified peak in admittance spectroscopy data, is not yet fully understood. Ultimately, this study aims to compile and analyze the NC reported in selected scientific studies, investigate the source of this phenomenon, and observe statistics in a general view.

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1. INTRODUCTION

The point where electronic technology has arrived currently, devices with large dimensions and slow, heavy, and rigid structures are being replaced by more compact, fast, light, and flexible ones. This rapid development draws attention to many electronic devices, especially FET, MOSFET, FinFETs, high-frequency Metal-Semiconductor (MS) Schottky Structures, several Schottky Junction Structures (SJSs) and their different interlayered types, solar cells, OLEDs, etc. Due to these structural changes in electronic devices, the negative capacitance (NC) phenomenon has been frequently observed in miniaturized electronic device applications in recent years (Joly et al., 2021; Karataş, 2021; Barkhordari et al., 2022; Liu et al., 2023; Çakıcı et al., 2023). With the Landau ferroelectric theory, ferroelectricity, which has been actively researched since the 1930s, has been employed quite commonly in the scientific community with the emergence of the negative capacitance phenomenon. Landau's theory, suitable for systems with long-range interactions such as ferroelectrics and superconductors, states that a system cannot change smoothly between two phases with different symmetries and that one phase must have higher symmetry than the other. However, negative capacitance effects were indirectly investigated but not fully revealed by researchers in the mid-1950s (Merz, 1956; Landauer, 1957).

To date, the perception of Negative capacitance has been generally described as an artificially created effect that has physical results in turn, similar to unexpected peak values in the device's electric and dielectric characteristics. NC has been explained by the feedback mechanism between applied voltage to the device and the altering value of the total device capacitance as "effective capacitance" by the polarization response of the ferroelectric material component due to the bias. Along with previous studies, in which the dielectric-

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ferroelectric series connected capacitors approach to adjust the gate voltage of structures was employed and is based on two stable states of polarization in elastic Gibbs free energy landscape, one of the latest studies highlighted how the negative capacitance can have different behaviors in different situations by theoretical changes. They offered a new approach in ferroelectric capacitors to have all the components of NC, including *transient NC*, for a better understanding of the real existence of this phenomenon by replacing the second-order derivative of elastic Gibbs free energy with the second-order derivative of electrostatic force work in related equations (Zhang et al., 2021). The NC effect was theoretically determined in quantum well-infrared photodetectors (QWIPs) by comparing experimental results with several methods, including the Incremental Charge Approach, Sinusoidal Steady-State Analysis (SSSA), and Fourier analysis. It was concluded that the incremental charge approach was unreliable for calculating a device's characteristics since this method lacked absolute rules for separating incremental charge distribution into positive and negative parts, which is critical for devices with more than two contacts and 2D or 3D geometric devices where the incremental dopant concentration is distributed throughout the device area (Ershov et al., 1998). This method was only suitable for very small current ranges in reverse bias regions of MS/MIS/MOS structures and for capacitance values in low frequencies. Although SSSA was a convenient approximation, they noted that all equations had to be calculated at each frequency to observe the frequency dependency of the capacitance. Since observing the physical causes behind the frequency response of a device's characteristics was more noticeable in the time domain, they used Fourier analysis, which shifts between frequency and time domains. Despite the challenge of accurately selecting the sample time, they only needed to calculate the capacitance and conductance equations once for all frequencies. Their solution found a correlation between experiments and numeric models based on simulation results. They also included the negative and positive parts of the transient response and summarized the capacitance formula as follows: $c(w) = c_0 + \frac{a_1 \cdot T_1}{1+(w \cdot T_1)^2} - \frac{a_2 \cdot T_2}{1+(w \cdot T_2)^2}$ Here, a1, a2, T1, and T2 are adjustable parameters, but they do not significantly affect the main capacitance. The capacitance C(w) converges to the geometric capacitance Co at high frequencies, while C(w) can be negative at lower frequencies due to the contribution of a positive-valued time-derivative of transient current in the time domain. The researchers also clarified the confusion about parasitic effects at different frequencies and suggested that if the NC appeared in high frequencies, it could be sourced from the external circuit and was not an NC effect.

In another study, the researchers paid attention to eliminating the aforementioned external circuit effects, which can affect observed NC in results, by counting on before and after open/short circuit calibration states (Joly et al., 2021). In their work, they produced several numbers of back-to-back contact Pt/ZnO/Pt SJ diodes by ALD for a microsensor system and observed the NC in their C-V plots, offering that the main reason for this effect was due to the impact loss process-related to the hot electron injection at the MS junctions' interface trap states. The other researchers compared two diodes and observed the NC in their interlayered Schottky structure's (Ag/$AgInSe_2$/p-Si/Ag) characteristics at forward bias and low-frequency region due to additional layer's surface modification effects (Çakıcı et al., 2023). In one of the interlayered works, a p-Si MIS-structured capacitor was fabricated and investigated, using Ta2O5 as the insulating layer, ZnO as the semiconductor layer, and Al for the metal contacts (Noh et al., 2003). The researchers observed that the dielectric layer showed a negative flat band voltage due to charge trapping behavior based on the existence of positive charges in the films under the constant current applied. When they compared stress-induced leakage current (SILC) for different amounts of time, they explained why the SILC, affected by a higher stressing time of current, could be sourced from the generation of localized charges and trap states near the injection interface. So, they explained the low interface state density, which is a key element for a MIS type structure for performance, according to the combination of interlayers they employed. Researchers, then, have started to investigate alternative ways of using the "NC phenomenon" to develop device's energy consumption characteristics by designing new combinations of atoms to reduce the voltage loss rather than keeping the subthreshold swing below 60 mV, Boltzmann limit, with the help of short channel effects. In 2008, the negative capacitance was suggested to decrease the sub-threshold slope below 60 mV/decade by replacing the gate oxide with a negative capacitance material. When the compared devices' layer of HZO was changed with a pure layer of HfO_2, the new structure improved its previous, current characteristics to two times greater on ION and ten times lower on IOFF for short-channel devices (Salahuddin & Datta, 2008). Replacing the gate oxide with a negative capacitance material in conventional transistors, lessening the necessary energy for the device can be provided by reducing the supply voltage through negative capacitance (Khan, 2015).

Studies on the NC phenomenon are encountered in the literature, especially in ferroelectric-dielectric structures (Hoffmann et al., 2019; Park et al., 2019; Migita et al., 2019; Yadav et al., 2019; Luk'yanchuk et al., 2019; Hoffmann et al.,2021b; Cheema et al., 2022). These studies aim to improve sub-threshold swing and internal voltage amplification. Instead of bulky inductors, capacitors with NC values can be evaluated in many different applications, such as providing broadband impedance matching in radio frequency applications (Tade et al., 2012). However, in several studies, NC has been observed at the different low, mid, or high-frequency ranges since the point defects, N_{ss}, material types, bandgap engineering approaches, growth techniques, etc., have been changed or investigated in more detail with the help of developing tools and theoretical approaches. In one study, the NC peaks were observed at all frequencies except two individual ones (C was just negative at 30 Hz and just positive at $8.1x10^4$ Hz) for a MIS type device, while the conductance values were at all frequencies positive only (Ashery, 2022). With the classification of physics behind the basic device parameters highly connected to the temperature and frequency, it was seen that the capacitance seen at low frequencies was caused by N_{ss}, which has great effectiveness in the conduction mechanism related to TFE. One of the latest studies shows that it can be achievable to decrease the gate oxide dimensions in electronic devices below equivalent oxide thickness (EOT). The researchers used an ultrathin HfO_2-ZrO_2 superlattice gate stack for this purpose and reached a 6.5 A thickness of EOT without mobility decline. It is very promising for future electronics (Cheema et al., 2022). To stabilize the NC effect on interlayered structures, researchers have been trying different compounds of atoms for interfacial layers or adjusting different variables of a material, similar to changing the thickness of a MOSFET gate and different density percentages of dopped atoms in an interlayer or replacing the gate oxide material with new ones. In one of the previous studies, it is mentioned that researchers changed the gate dielectric material of a Si-based MOSFET from SiO_2 to SiON so they could achieve decreasing the dimension of gate oxide below the EOT for lowering the switch voltage between on and off by increasing the ε_r. In the following years, even the usage of dielectric materials became the new "necessity" to provide a higher ε_r to continue for better scaling of EOT (Hoffmann et al.,2021a). However, the physical limitations of the nature of structures have not allowed this reduction by changing the dimensions to below minimum according to loss of reliability and implementation of device characteristics until the new founds on ultrathin superlattice gate material of transistors (Cheema et al., 2022). In another study, researchers explored Al/Ag/Al_2O_3/TiN structure for two different thicknesses at 20 nm and 5 nm, respectively, and reached the results that different thicknesses of Al_2O_3 can change the switching performance and dipole uniformity of a CBRAM according to its changing ferroelectric characteristics. So, with the help of this rising ferroelectricity by reducing the thickness of the Al_2O_3 because of the more diffusing ionized Ag atoms into the thinner layer. So, this layer shows NC effects because of the phase change rather than geometric capacitance. And as a result, this ferroelectric behavior will help many kinds of memory units to store big data and fast controllability (Senapati et al., 2020). Several researchers have also been interested in modeling or determining the NC and finding numerical models for predictions on materials, which can be favorable for usage and production of what technology brings next in non-linear behavioral structures. Since many NC observed structures in literature generally have a common tendency to have NC at lower frequencies and forward bias, a model modification was offered on Barna and Horelick (BH) recombination diode model, employing a variable series resistance effect, which may stem from the reducing intrinsic carrier concentration after comparing the surface states and BH model due to its adaptation is more flexible to related solar cell structures (Bisquert, 2011). In a recent work, the authors used Miller Model (MM) combined with Poisson equations to make a blueprint model of how the NC effects can be changed and observed by means of the MM since it has more flexibility compared to the LM which cannot catch or present the different directional switches by fitting on just one S curve (Lee & Yoon, 2022). To do so, for a FE–DE capacitor, they divided, as a theoretical/numerical approach, the structure into local polarization zones into an aligned dots-like shape for better investigation. So, they would be able to observe the average polarization response around a dot to the applied field in scale determined. They did not include domain interactions between these little dots since the FE layer of the FE-DE combination would exhibit almost a uniform electric field. They concluded that if the ferroelectric layer is used with a dielectric layer, the FE will have more sudden polarization changes resulting in increased effects of NC behavior. Also, the FE layer's dimensions can be considered an improvement in NC when it is thicker due to simulation. Other findings were that the smaller the coercive field (EC) and remnant polarization (PR) values, the narrower the hysteresis curve range was. As long as the polarization can be manipulated, which in turn will make it possible to get a higher effective capacitance and a lower bias necessity and so a smaller SS in the ferroelectric material's structures by the help of domain walls' energy or other parameters mostly effective on switching directions and spin moment and so on, not only Boltzmann limit can be achieved, but also other limitations will be able to overcome. This concept within a study, was achieved a hysteresis-free transition behavior at a subthreshold swing (SS) as small as 9.7 mV without a DE layer attached to the structure’s FE layer (Song et al., 2022). In another study, the researchers explored Pt nanosheets' effects on MgSe thin films, revealing enhancements in light absorbability, energy band red-shift, and decreased dielectric constants, while sandwiching MgSe between Pt layers enabled the creation of tunneling-type diodes with negative capacitance properties, indicating potential applications in parasitic capacitance mitigation, noise reduction, and microwave resonance (Algarni et al., 2022).

When it was first searched for the negative capacitance in this study, it was realized that this phenomenon is strongly related to all these structures: MS, MPS, MIS, MFS(MFMIS, MFIS, and so on), and it was expected that it has the potential to be a building block property for many others which have not been invented or fabricated yet. All these structures need insulating or interfacial dielectric layers, except just directly MS contact ones like some Schottky barrier diodes. In the literature, mostly III-V or II-VI groups of compounds from the periodic table have been used when Schottky structures are prepared. Moreover, hafnium zirconium oxide (HZO) related variations of interlayers have been generally preferred for ferroelectric-based structures like NC-Fets and capacitors, as well as in ferroelectric tunnel junctions (FJTs) according to both industrial background and good features (Khosla & Sharma, 2021; Li et al., 2021; Segatto et al., 2022). Also, polyvinyl alcohol (PVA) has been lately attracting researchers and thought for usage in Organic field-effect transistors (OFETs), MPS-type structures, and capacitors for its capability of thin- film fabrication, specialties in usage processes such as effortlessly dissolving in water or alcohol, and by being nontoxic, a wide range of crystallinity, having high dielectric strength, and reasonable charge storage capacity, and fast eliminating the oxidation of surfaces specialty for better conduction by its formation. (Ashery et al., 2021; Demirezen & Yerişkin, 2021; Kaur et al., 2020; Alsmael et al., 2022). In 2021, researchers investigated a PVA/nSi Schottky barrier device for its electrical characteristics dependent on temperature. Some results, which are highly related to NC, showed that the increase in barrier height and ideality factor values could be sourced from the specific characterization of the interface situations (Ashery et al., 2021). In another study, the use of PVC and PVC:SnS interlayers in MPS-based SBDs was found to contribute to the observed negative capacitance at low frequencies, a phenomenon attributed to the presence of these doped or undoped interlayers, as well as the saturation effect of interfacial trap levels at the crossover frequency and the differential effect of the electric charge (Q) (Barkhordari et al., 2022).

Recently, a study group made one of the most straightforward explanations for the act of NC by directly measuring it in a Pt/BTO/Si/Pt structure with a total capacitance change by an interplay between geometric capacitance and additional capacitance, which is formed due to the bias change that is effective on charge moves related to oxygen vacancy migration, interface charge injection, interface depletion layer, and polarization switching (Liu et al., 2023). They presented the total capacitance changes according to altering relaxation components and bias response of charges from small to large scale of polarizations for both positive,0, and negative voltages on device response and observed the tunable NC effect under low frequency and large polarization. They concluded that the total capacitance can be tuned by adjusting the contribution of relaxation parameters with different voltages, specifically on the ferroelectric/semiconductor part.

In light of all these findings, it has become a necessity to determine the ratio of the produced, simulated, or modeled structure publications related to MS-NC among themselves in order to understand the general trend and its causes in the main structures in which NC is observed. In this study, basic subgroup classification was made with the help of a support vector machine (SVM) algorithm in order to see under which structure the existing studies in the literature are gathered.

2. MATERIAL AND METHOD

The data was acquired from the Web of Science (WOS) database for the last 20 years, excluding pre-prints, as a result of scanning the academic studies on NC behavior in certain electronic devices worldwide and in Türkiye and were transferred to an excel file and analyzed with statistical distributions by years, sub-structures, and countries. We prepared the training data according to most related terms in categories or sub-categories related to literature. Initially, the FNC filter (just NC terms) was applied to identify all NC studies, resulting in 2613 NC-related records. Subsequently, the FMS filter (NC and MS, MIS, MFS, MPS terms) yielded 276 records related to both NC and MS. These studies were then further sorted in the WOS database: the 2613 records were reduced to 2483 records by cleaning unrelated or repeating ones, while the 276 records were categorized using a more specific method. Since all 2483 records have both MS-NC and other types of NC-related structures, mostly including FET data, we did not share that classification results of the 2483 records distribution in this study. Since sorting searches were giving interwoven sub-categories of structures all together in databases, it was necessary to cluster them into more precise numbers of categories to determine the most realistic record numbers. So, these studies were categorized using a classification code, which is given below, into their sub-structures to investigate how the differently structured materials show NC behavior. We preferred to use a SVM since when K-means is used, it will only give the numbers of random labels no matter what they are. It is necessary to say when trained SVD and then K-means are used together or just K-means and elbow method are used in the algorithm they give closer numbers to WOS results but since the labels should be clear up to the sub-categories, it was not preferred. Since a study showed that a combination of SVD and SVM algorithms gave better accuracy when used together than just SVM used itself, we preferred a similar way as in their work by employing the favors of SVD by dimension reduction (., & Rarasati , 2022). When using the data tables for both training and testing, we employed the same index terms for training as the same as in the WOS search. For the classification of the datasets, text data in two columns of records for each study were used as "article title" and "abstract." other data of records (except publication years), like authors, etc., were excluded since they did not have the necessary information in them. Other details can be accessed from the supplementary document. The study process is given in Figure 1 below. This work primarily focused on drawing a general picture of the NC observations and how related studies are distributed statistically. However, since it is a general view for specifically count on MS-NC studies, it was not mentioned how the FETs, high-k materials, ferroelectric behavior basics, spintronics, and other approaches to the field have been affecting, which may be a topic for another paper.

Classifying script's Pseudocode Steps:

1. Import necessary libraries such as: Pandas, TruncatedSVD, TfidfVectorizer, and SVM.

2. Read in the training and testing data from Excel files using Pandas read_excel function.

3. Train a TruncatedSVD model on the training data. TfidfVectorizer is used to convert the text data into a matrix of TF-IDF features. TruncatedSVD is then applied to the transformed training data to reduce the number of dimensions to n=13(n selected for best accuracy according to feature numbers).

4. Apply the trained TruncatedSVD on the testing data.

5. Use SVM to classify the testing data. An SVM model is trained on the reduced training data using the SVM class from scikit-learn with a linear kernel.(rbf, poly, sigmoid were also tried besides linear kernel but empirically 'linear' gave better results than rest). The trained SVM model is then used to make predictions on the reduced test data.

6. Map predicted label numbers to their corresponding names using a dictionary.

7. Create a Pandas DataFrame of the predicted labels and write to an Excel file named 'Predictions.xlsx'.

8. Print the count of each predicted label.

9. Evaluation of the classifier through comparing the predicted labels and true labels.

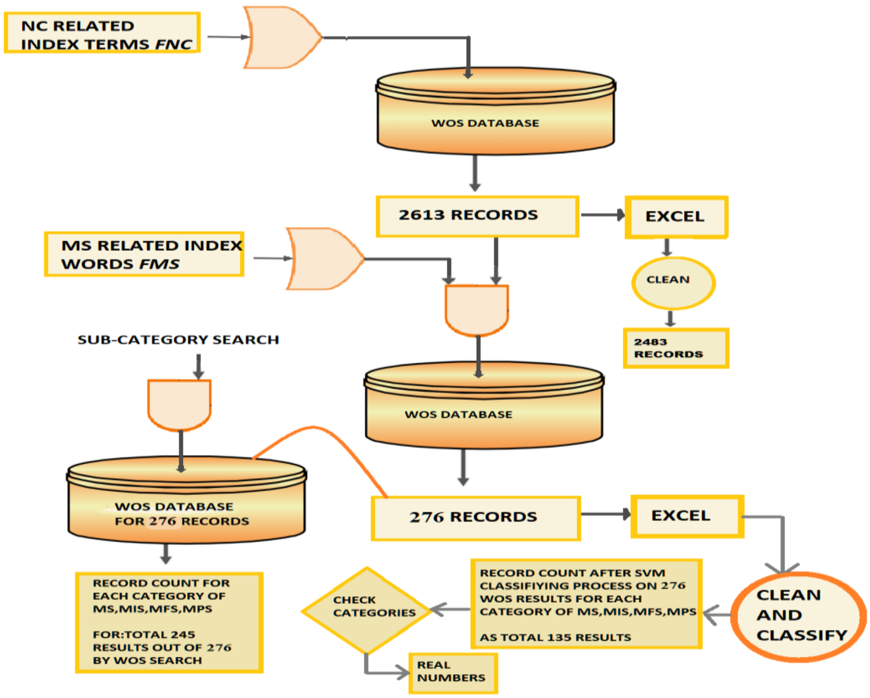

***Figure 1.** Study research process with our filtering terms in the WOS index and classifying in script*

3. RESULTS AND DISCUSSION

The NC phenomenon, whose presence in MS structures was previously attributed to parameters such as surface states and series resistance as well as instrumental problems, noticed as an ill-defined peak and described as an abnormal and explained as an inductive behavior of the material, has become increasingly popular in the scientific community, thanks to a better understanding of its origin and advantageous properties especially at ferroelectric-based devices in recent years (Tan et al., 2017). From this point of view, this study sheds light on the meaning of the presence of NC in both MS structures and other structures, and the statistical distribution of studies in this field is interpreted with the figures below. In the last fifteen years, especially after 2015, the prominence of advantageous features such as reduce subthreshold swing and power supply voltage, improve static noise margin, voltage gating, low power dissipation and low threshold voltage has enabled the intensification of scientific studies on the NC phenomenon.

The small differences between record counts in Figure 2 are sourced from cleaning unrelated or repeating articles for corrections in articles. Figure 3 and Figure 4 show that MS-related (generally comprised of interlayered structures like diodes, solar cells, capacitors, and heterostructures excluding most of the 3-leg devices) NC studies have increased over the years. However, the ratio of the rising number of studies in these plots is lower than the general NC studies in Figure 2, since most researchers have been focusing on new materials related to multi-layered structures (like FETs and so on) in general NC works. Moreover, the MS-related search result of WOS also had unrelated records in Figure 3; after a small data cleaning, we obtained 135 directly related records out of 276 total results in Figure 4. In these records, many heterostructures were not described as a specific structure in their data columns, and they were included or excluded according to their consistency of metal and semiconductor parts in a structure somewhat together. So, the 135 records distribution in Figure 4 has only MS-related NC records. Also, the number of studies is expected to be higher by the end of this year since this work includes the dataset until August 2023.

The rapid increase after 2015, seen in both Figure 2, Figure 3, and Figure 4, started to rise cumulatively due to the findings of a previous study by the researchers (Salahuddin & Datta, 2008). After achieving SS reduction, the academy and the industry have turned their interests into different device designs with ferroelectric materials and other new compounds to employ in heterostructures to develop these re-discovered figures of merits, specifically for the polarized-layered structures. So, the rising trend in Figure 2 explains the ferroelectric behavior based on complex devices' designs, fabrications, and investigations (Iwashige et al., 2023). Also, they include other types of devices, like MS-based ones, but with a slight impact on the statistics. When looking at Figure 4, the MS-NC studies become prominent in the statistics. They shape this rising trend in records due to the employing of new or non-used materials, fabrication methods, and materials already in use for the aforementioned re-discovered field (Saghrouni et al., 2015; Poklonski et al., 2023).

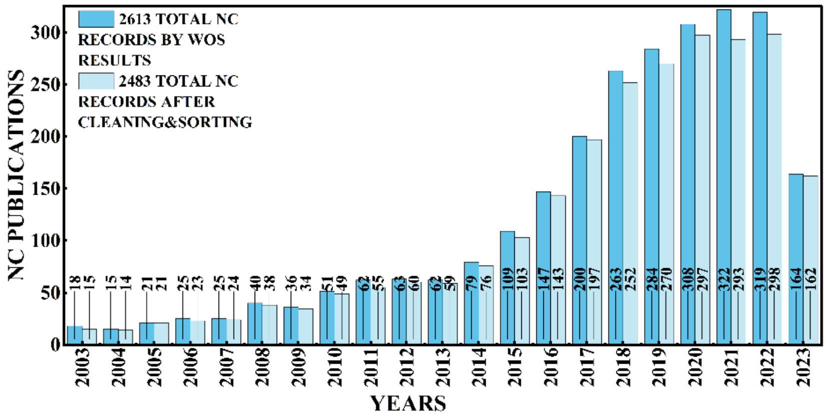

Figure 2. *The Publication counts on general NC studies*

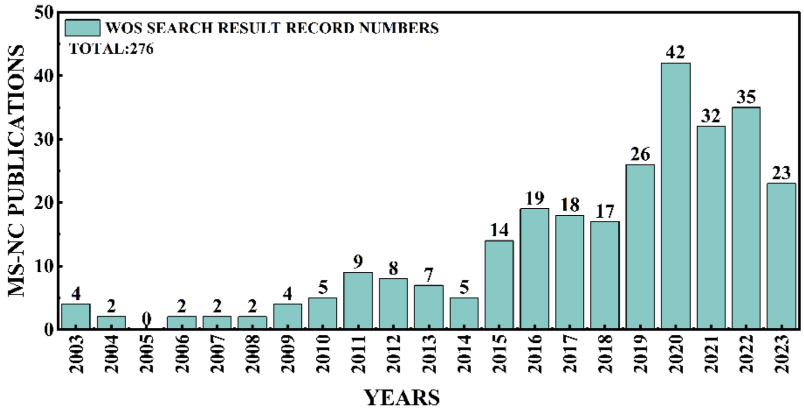

Figure 3. *Total 276 WOS results for MS-NC studies*

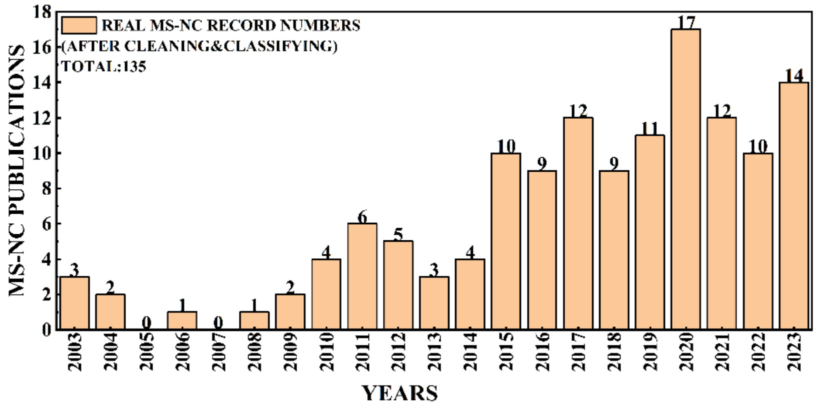

Figure 4. *Total 135 results for MS-NC studies after cleaning and classifying*

As seen in Figure 5, China is at the top of the countries studying NC by 867 records. Moreover, the USA and India follow, respectively. The most important reason for this may be the excess number of researchers and research opportunities in these three countries and the amount of field marketplace. Türkiye ranks 8th among the countries in general NC publications, which shows that the researchers in Türkiye are interested in non-linear behaviors like NC of interlayered structures. This result may arise from the fact that the follow-up project funds are getting broader for this field or that the universities find this sub-field more attractive due to the developments of these fundamental structures having an interplay in future mass production opportunities.

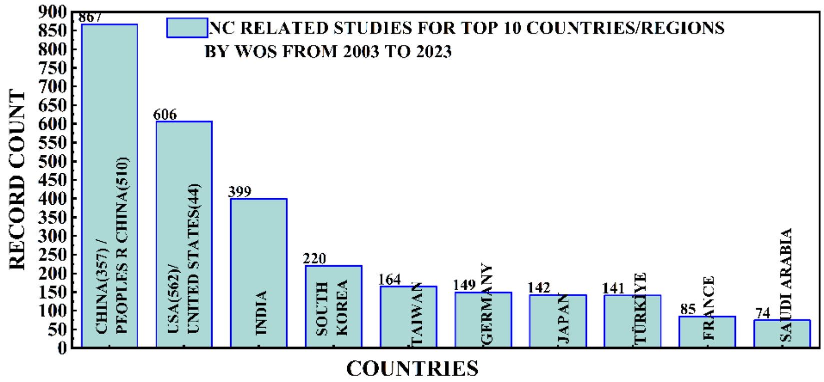

Figure 5. *The Publication counts by top 10 countries on general NC studies*

Figure 6 shows that Türkiye is focused on metal-semiconductor structures and has observed NC-related behavior 68 times in MS-NC studies so far among the other countries. At the same time, China has the first seat with 69 total records, and India is in the third seat with 63 publications.

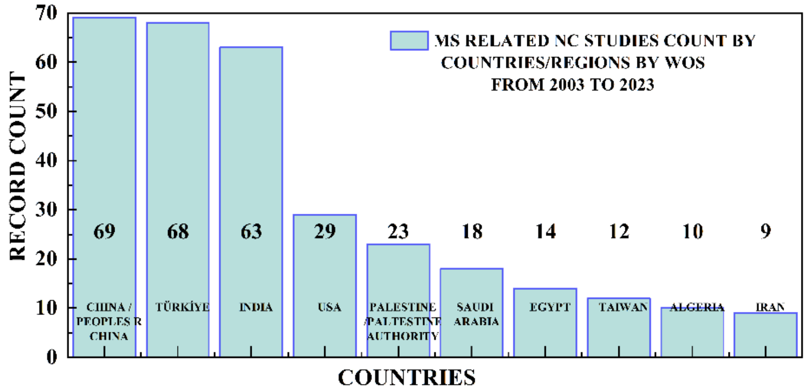

Figure 6. *MS related NC works distribution by countries*

Figure 7 shows that in Türkiye, this phenomenon *NC* takes more attention with time. The reason for that may be considered as the "surface states" come with the results of rising studies of interlayered MS structures, specifically reported Schottky structures studied in Türkiye.

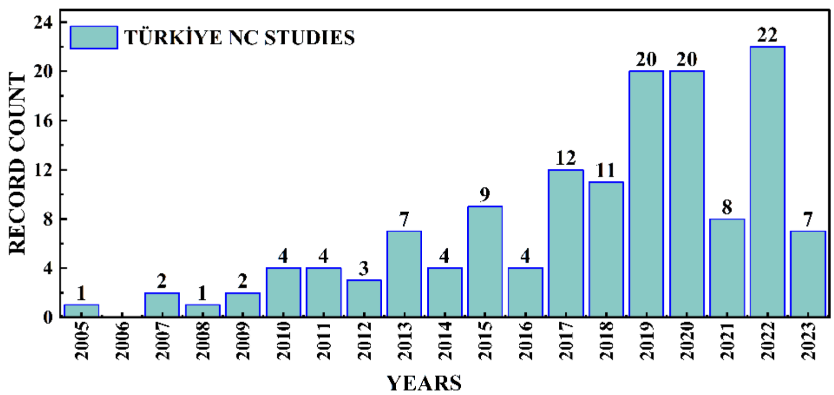

Figure 7. *The NC Publication counts in Türkiye by years*

The giant pies for NC studies in Figure 8 belong to the fields of Engineering, Physics, and Materials Science. The reason engineering is on the highest side of the group may be the developments related to memory devices' sub-parts, like all kinds of switching components with different gate designs. However, with surface/additive engineering studies, optics and computer science are growing, too. The rise of the tendency to search for NC and ferroelectricity among scientists is promising for future applications. Nevertheless, it is still underrated compared to other research areas in semiconductor-related fields. As seen in Figure 9, Physics has a key role in MS-NC works since the structures' modeling, fabrication, and investigation processes employ many inter-disciplines, such as with the Physics theorems from ion-scattering, even more from electron's spin moment, quantum mechanics approaches to the compounds, interlayers, defects. Thus, this field has the highest second-record number among the others on MS-NC. Also, of course, all these research areas have intertwined with each other. The difference in the research field distribution up to MS and MS-NC Figure 8 and Figure 9 might be attributed to the fact that engineering is more interested in using devices that are more complicated and multilayered, such as FETs, as building blocks for bigger device systems, which has a big pie in literature, while physics is more interested in solving the basics behind why all these structures have different or similar characteristics or their tendency to develop new basic structures as samples for better options to use in more complicated ones. Also, computer-aided design developments should have contributed to this result.

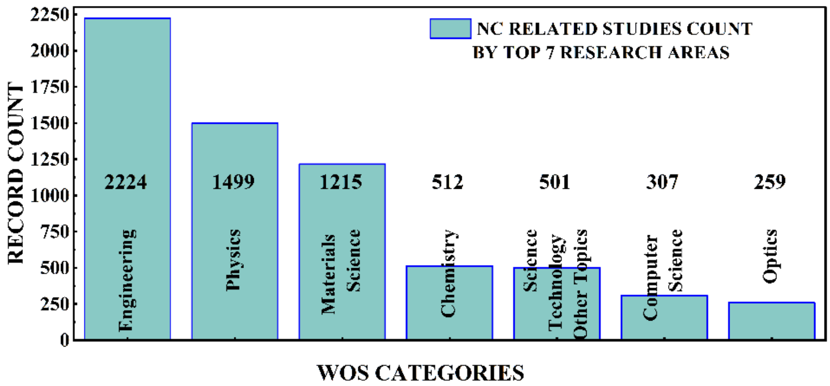

Figure 8. *The distribution of publications on distinct research areas in WOS categories for general NC studies*

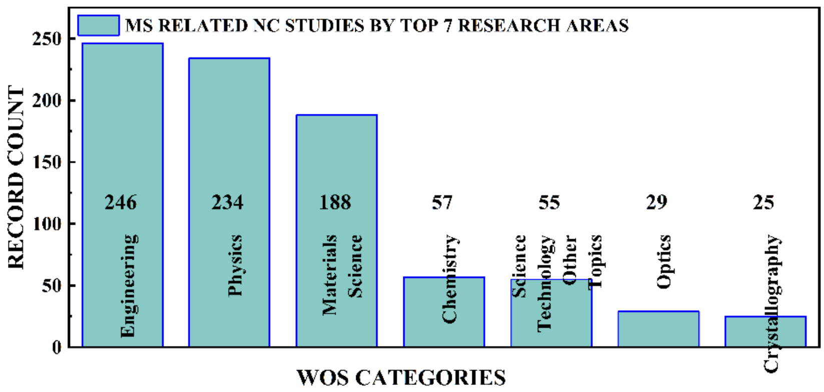

Figure 9. *The distribution of publications on distinct research areas in WOS categories for MS related NC studies*

This study showed that NC-MS-related studies have been chiefly on MS and MIS-type structures in Figure 10. However, one shall notice that MS structures have a big pie in all statistics because most structures have metal and semiconductor contacts, so the ratio of the sub-structures is manipulated by common MS terms in databases since MS includes all other categories. It also shows that Schottky barrier junction studies can have a big pie in this sub-research field. The deviation in the WOS search, which gives 276 results for MS-NC studies for a total and 245 for a total of each subcategory, is because these 276 studies have unrelated records like specific ferroelectric or polymer or another type of multi-layered structures that belong to another sub-field of NC-related works. Also, these structures have interwoven categories, so the actual numbers of records are not clearly represented in general database searches. According to these compared results, researchers have studied 135 MS-NC-related works. The deviation of WOS from the actual MIS records numbers may stem from MIS structures that can include MPSs and MFSs. The deviation of classification from real numbers in MIS stems from mismatching with MS structures since MS has common terms for all categories, while the datasets for abstracts and titles need more specified unique keywords for testing. Also, the WOS deviation in MFS may stem from ferroelectric material configuration-based FET-like miscategorized structures that exist in the database when they should have been excluded instead. The deviation in MFS for classification results stems from the ferroelectric-based words, which are not used in the proper configuration as ferroelectric between M and S layers, while the text data still has these materials in as a whole combination. Also, the non-functional word groups in texts affect the training SVD since some of them are specifically necessary to define a structure like the word "with" as a matrix feature; pointing on an "interlayer" cannot be used as stop words to eliminate in algorithm while many of them are useless in the rest of the text.

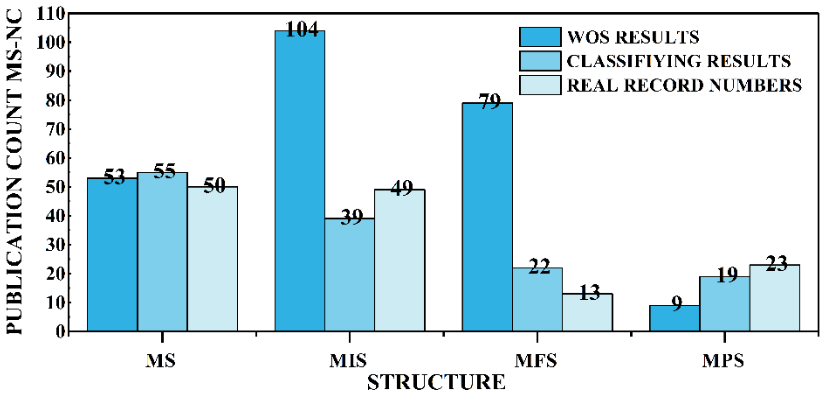

Figure 10. *The distribution comparison of MS-NC publications as MS,MIS,MPS,MFS by WOS search, classifying and real records after label checking*

Perovskite oxides mainly contribute to MFS interlayers in capacitors, solar cells, and gate stacks, while PVC/PVA-related materials are essential for MPS structures besides high-tech carbon orderings. MIS structures have a broad range of interlayers, primarily employing oxide compounds, while they also share the structure type of mainly SBDs with the MPS group. A detailed list of publications generally presented in Figure 11, including these materials, can be reached directly from the WOS database, or supporting documentation.

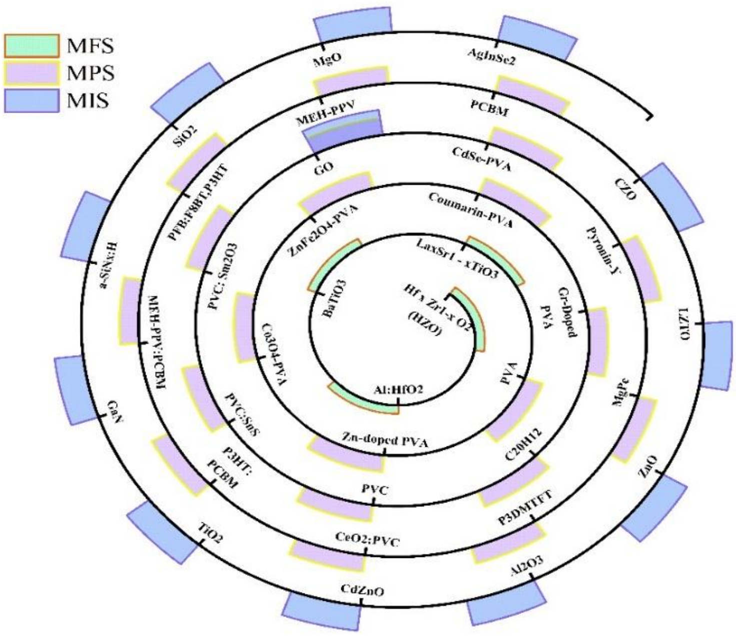

Figure 11. *Interlayer materials used in MS-NC studies for three sub-categories*

4. CONCLUSION

In this study, a general statement was given for NC observed MS publications with the help of statistical analyses made by an SVM algorithm, finding a realistic distribution of publications besides employing database statistics up to August 2023. After explaining the existence of NC and its advantages clearly, statistical data emphasized that the number of publications related to NC worldwide and in Turkey has increased over the years. It was observed that 5.68% of the total 2483 records in NC are publications containing Turkey's contribution. With a total of 65 publications, with 53 directly studied in Türkiye and 12 contributions to other countries, Türkiye has a share of 48,15% on MS-related-NC records in a total of 135 classified works. These ratios can be interpreted as a result of the high number of study groups working on NC in MS structures in Türkiye and the fact that the NC phenomenon has become a popular field of study in recent years. Based on the examined MS-related articles in the literature, it can be concluded that NC appears mostly at forward bias and low frequencies due to dipole relaxation times. Surface states affect NC appearance at low frequencies, and decreasing sub-threshold voltage has been a game changer in low power consumption and speed switch applications. NC has been used as a manufacturing parameter for memory-cell production and investigated for filament formations and breakages in resistive switching. The specific arrangement and thickness of layers in a Schottky diode can determine its electrical characteristics, and Spintronics research can also be relevant. Scientific studies on NC are expected to increase and NC phenomenon is expected to play a critical role in electronics technology.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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