Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης

Δράση ΕΡΕΥΝΩ – ΔΗΜΙΟΥΡΓΩ – ΚΑΙΝΟΤΟΜΩ

Συγχρηματοδότηση από την Ευρωπαϊκή Ένωση και τους εθνικούς πόρους μέσω του Ε.Π. Ανταγωνιστικότητα, Επιχειρηματικότητα & Καινοτομία (ΕΠΑνΕΚ)

# RADAR

“ Ετερογενής Τρισδιάστατη Ολοκλήρωση με χρήση ρηξικέλευθων νανοτεχνολογιών για τη νέα γενιά μικροκυματικών πομποδεκτών ισχύος ”

**Κωδικός έργου: Τ1ΕΔΚ-00329**

## Ενότητα Εργασίας 3: ΤΕΧΝΟΛΟΓΙΚΑ ΠΡΩΤΟΚΟΛΛΑ

## Παραδοτέο 3.6 - M12

## Ετήσιες δράσεις διάχυσης της ΕΕ3

**Ημερομηνία : M12**

**Επικεφαλής παραδοτέου: ΙΤΕ**

**Συμμετέχοντες**

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**GLONATECH:** Β. Βαμβακάς

**ΙΝΝ:** Π. Δημητράκης, Pascal Normand, Βασίλειος Ιωάννου-Σουγλερίδης

**ΕΚΠΑ:** Γ. Παπαϊωάννου, Δ. Μπιρμπιλιώτης, Μ. Κουτσουρέλη, Γ. Θεοχάρης

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**ΑΜΕΝ:** Δ. Νιάρχος, Κ. Καρυοφύλλης

# 1. Αντικείμενο της Αναφοράς

Αντικείμενο της παρούσας αναφοράς είναι η καταγραφή των ενεργειών που έχουν γίνει κατά τη διάρκεια του πρώτου έτους του προγράμματος για τη διάχυση των αποτελεσμάτων της έρευνας στα πλαίσια της ΕΕ3 του ΡΑΝΤΑΡ. Είναι αναμενόμενο η ποσότητα των ενεργειών αυτών να είναι σχετικά περιορισμένη για τους πρώτους 12 μήνες.

Αρχικά δημιουργήθηκε το ΙΤΕ ιστότοπος που είναι συνεχώς ενημερωμένος. Ο ιστότοπος παρουσιάζει τα προφίλ των εταίρων της κοινοπραξίας και τις δράσεις διάχυσης. Η τακτική προώθηση των ειδήσεων και των εκδηλώσεων του έργου γίνεται μέσω αυτού που θα παραμείνει ενεργός για τουλάχιστον τέσσερα ακόμη χρόνια.

Η κοινοπραξία φροντίζει τα αποτελέσματα να δημοσιεύονται σε περιοδικά μεγάλου αντικτύπου και να ανακοινώνονται σε σημαντικά διεθνή συνέδρια.

Επίσης, στόχος της κοινοπραξίας είναι η διάδοση των επιτευγμάτων του έργου σε διεθνή τεχνικά φόρουμ και σε ημερίδες στα πλαίσια των δράσεων της εθνικής υποδομής Innovation-EL και της ελληνικής επιστημονικής εταιρείας Micro & Nano. Επιπλέον θα γίνουν προσπάθειες για διάχυση προς τις σχετικές βιομηχανικές και ακαδημαϊκές οργανώσεις Public-Private Partnership (PPP clusters) της ΕΕ και άλλους φορείς όπως η European Defense Agency (EDA).

Η κοινοπραξία προτίθεται να οργανώσει θεματική ημερίδα για να διαφημίσει τα τεχνικά και επιστημονικά επιτεύγματα του έργου.

Οι δραστηριότητες προβολής του έργου και διάχυσης των αποτελεσμάτων του έργου περιλαμβάνουν και συμμετοχή σε εκδηλώσεις "ανοικτής ημέρας", παρουσιάσεις και ομιλίες κατά τη διάρκεια της "Βραδιάς του Ευρωπαίου Ερευνητή" και της "Μάθε περισσότερα, γίνε καλύτερος" εκπαιδευτικές δράσεις αφιερωμένες στα σχολεία. Φυλλάδια και δελτία θα παρουσιάζουν εκλαϊκευμένα τα αποτελέσματα του έργου στο ευρύ κοινό.

# 2. Ιστότοπος "RADAR"

## 2.1. ΕΙΣΑΓΩΓΗ

Ο ιστότοπος "RADAR" σχεδιάστηκε για να παρέχει πληροφορίες σχετικά με το έργο και για το πώς θα επιτευχθούν οι στόχοι του. Ο ιστότοπος του έργου "RADAR" διατίθεται στο https://radar-project.iesl.forth.gr/ και είναι προσβάσιμο από κινητές συσκευές. Ο ιστότοπος σχεδιάστηκε για να αναθεωρεί και να αναπτύσσει συνεχώς τις δραστηριότητες διάδοσης στο πλαίσιο του έργου και να επιτρέπει συνεχή βελτίωση.

Ο δικτυακός τόπος περιλαμβάνει δύο διαφορετικούς τομείς, αφενός, έναν ιδιωτικό χώρο, ο οποίος χρησιμοποιείται κυρίως ως χώρος αποθήκευσης εγγράφων και ανταλλαγής διαβαθμισμένων πληροφοριών και, αφετέρου, δημόσιος χώρος. Ο δημόσιος χώρος του ιστότοπου θα προωθήσει το έργο "RADAR" μέσω σχετικών πληροφοριών, συμπεριλαμβανομένων των στόχων του έργου, του ιστορικού εταίρου και των μη ταξινομημένων αποτελεσμάτων του έργου.

Όλοι οι εταίροι θα συμμετάσχουν συλλογικά στην επικαιροποίηση διάδοσης της ιστοσελίδας παρέχοντας ενημερωμένες πληροφορίες

## 2.2. ΣΧΕΔΙΑΣΜΟΣ, ΣΥΝΤΗΡΗΣΗ ΚΑΙ ΕΝΗΜΕΡΩΣΗ

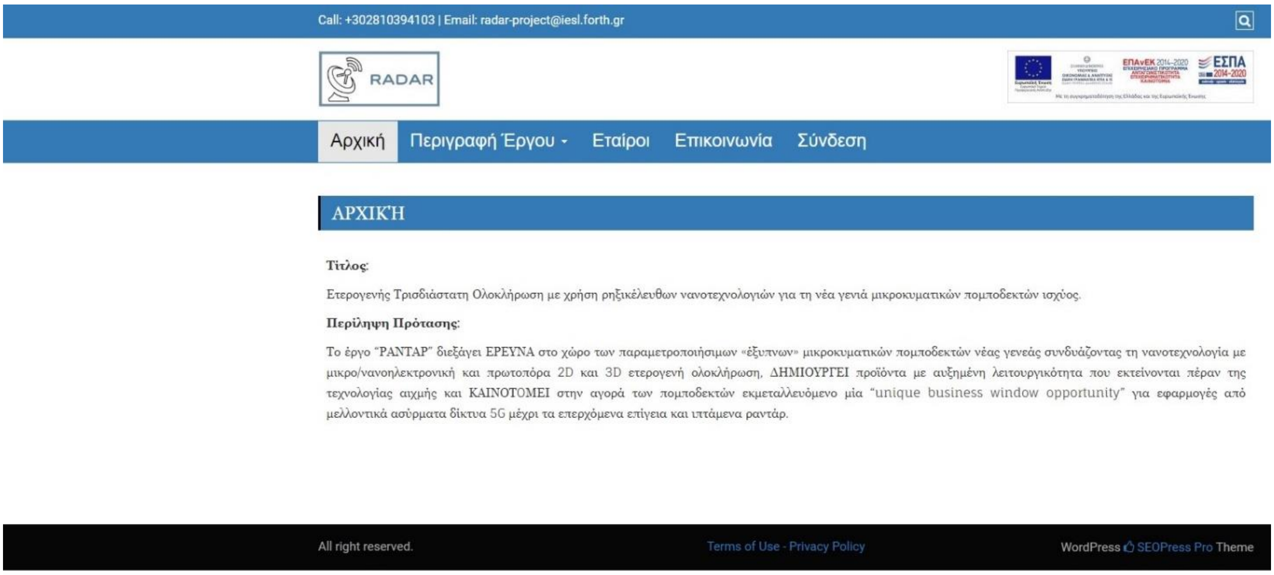
Ο ιστότοπος σχεδιάστηκε με έναν εύκολο τρόπο πλοήγησης, ο οποίος επιτρέπει στους χρήστες του ιστότοπου να μάθουν για το έργο και τα αποτελέσματά του, ειδήσεις κλπ. Όλα τα τμήματα του ιστότοπου έχουν στην κορυφή το λογότυπο RADAR (στα αριστερά) και μια αναφορά στη χρηματοδότηση εργαλεία (στα δεξιά).

Η ιστοσελίδα φιλοξενείται και διοικείται από την Ομάδα Μικροηλεκτρονικής Έρευνας (MRG) του Ινστιτούτου Ηλεκτρονικής Δομής και Λέιζερ (IESL) του Ιδρύματος Τεχνολογίας και Έρευνας (ITE). Ένα αφοσιωμένο μέλος του προσωπικού της MRG επικαιροποιεί τακτικά τον ιστότοπο, μοιράζεται ειδήσεις, πληροφορίες σχετικά με εκδηλώσεις του έργου, παρουσιάσεις και άλλα σχετικά με το υλικό του έργου.

Ο ιστότοπος κατασκευάστηκε χρησιμοποιώντας το WordPress. Το WordPress είναι ένα ελεύθερο και ανοικτού κώδικα σύστημα διαχείρισης περιεχομένου (CMS) βασισμένο σε PHP και MySQL. Μεταξύ άλλων πλατφορμών, το Wordpress είναι μια δημοφιλής, καλά υποστηριζόμενη πλατφόρμα δημοσίευσης blogging και έχει μια μεγάλη κοινότητα που θα ελαχιστοποιήσει το ποσό της πολύπλοκης προσαρμογής που θα χρειαστεί να κάνει ο Συνεργάτης του Έργου.

## 2.3. ΔΙΑΡΘΡΩΣΗ ΙΣΤΟΣΕΛΙΔΑΣ

Ο δημόσιος χώρος έχει σχεδιαστεί για να εξασφαλίσει τη δημόσια προβολή των επιτευγμάτων και των αποτελεσμάτων του RADAR. Ο δημόσιος χώρος περιλαμβάνει πέντε κύριες σελίδες, όπως φαίνεται στο Σχήμα 1: Αρχική σελίδα, περιγραφή της εργασίας, συνεργάτες, διάδοση, επικοινωνία και μια καρτέλα "Σύνδεση" για να έχουν πρόσβαση οι συνεργάτες στην ιδιωτική περιοχή (προστατεύεται με κωδικό πρόσβασης). Αγγλικά είναι η γλώσσα που επιλέξατε.

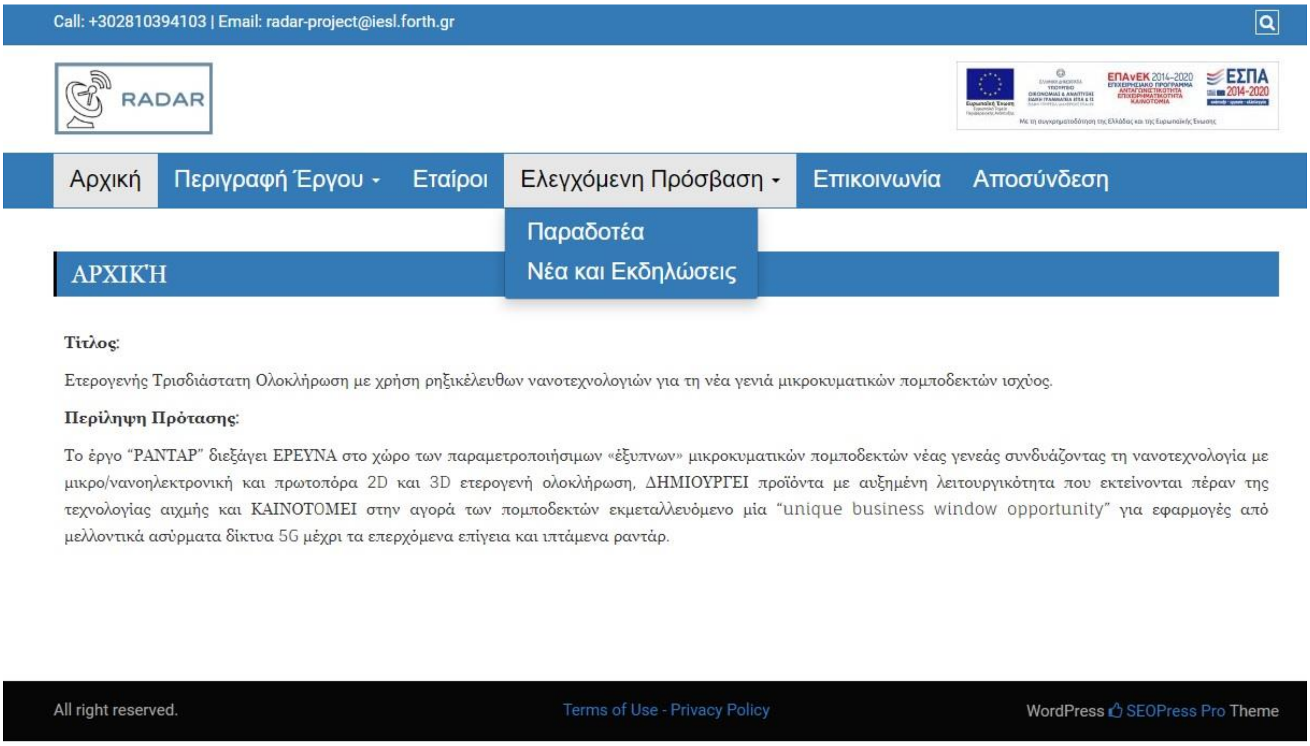



**Σχήμα 1:** Στιγμιότυπο οθόνης της αρχικής σελίδας του ιστότοπου "RADAR"

- Η σελίδα **«Αρχική»** παρέχει γενικές πληροφορίες για το έργο «RADAR».
- Η σελίδα **«Περιγραφή Έργου»** παρουσιάζει το αντικείμενο, τους στόχους και την μεθοδολογία υλοποίησης του έργου.
- Η σελίδα **«Εταίροι»** παρουσιάζει τις επωνυμίες των εταίρων που συμμετέχουν στο έργο, καθώς και τις συντομογραφίες μαζί με τις περιφέρειες του κάθε φορέα.
- Η σελίδα **«Επικοινωνία»** παρουσιάζει πληροφορίες (τηλέφωνα και διεύθυνση επικοινωνίας) που σχετίζονται με τον συντονιστή του προγράμματος.
- Η σελίδα **«Σύνδεση»** δίνει την δυνατότητα πρόσβασης στην ιδιωτική περιοχή του έργου «RADAR». Οι εταίροι ανακατευθύνονται στη σελίδα σύνδεσης και ζητούν τη σύνδεσή τους και τον κωδικό πρόσβασής τους για να μπουν στην περιοχή.

Ο ιδιωτικός χώρος έχει σχεδιαστεί ως μια ενιαία πλατφόρμα εργασίας μόνο για εξουσιοδοτημένους χρήστες μόνο. Ο χώρος αυτός χρησιμοποιείται για την κοινή χρήση όλων των εμπιστευτικών εγγράφων και η πρόσβαση σε αυτήν απαιτεί διαδικασία σύνδεσης όπου όλοι οι εταίροι έχουν λάβει ο καθένας ξεχωριστά από ένα αναγνωριστικό ονόματος και κωδικό πρόσβασης. Στα παρακάτω Σχήματα 2 και 3 είναι στιγμιότυπα οθόνης της ιστοσελίδας του Έργου «RADAR».


**Σχήμα 2:** Για να έχει κάποιος χρήστης/εταίρος πρόσβαση στην ελεγχόμενη περιοχή της ιστοσελίδας, θα πρέπει να κάνει σύνδεση με χρήση ονόματος και κωδικού που του έχει δοθεί από τον διαχειριστή της ιστοσελίδας.




**Σχήμα 3:** Ο χρήστης/εταίρος της ιστοσελίδας όταν συνδεθεί επιτυχώς στην ελεγχόμενη περιοχή έχει πρόσβαση στις κατηγορίες «Παραδοτέα» και «Νέα και Εκδηλώσεις»

## 3. Δημοσιεύσεις σε διεθνή περιοδικά και συνέδρια (acknowledging RADAR)

### 3.1. Διεθνή Περιοδικά

1. D. Birbiliotis, G. Stavrinidis, M. Koutsoureli, G. Konstantinidis, G. Papaioannou, A. Ziaei, “A comparative study of nanostructured Silicon-Nitride electrical properties for potential application in RF-MEMS capacitive switches”, ELSEVIER, Microelectronics Reliability, 100-101, 2019

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A comparative study of nanostructured Silicon-Nitride electrical properties for potential application in RF-MEMS capacitive switches

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ABSTRACT

The present paper aims to investigate the electrical properties of nanostructured SiNx with embedded (i) CNTs of random orientation, (ii) columnar bunches of vertically aligned CNTs and (iii) columnar Au nanorods. MIM capacitors were used to assess the effect of dielectric film structure on the electrical properties. The charge transport mechanism was assessed through current - voltage characteristics and the charge draining efficiency through the top electrode potential decay. In the case of random oriented CNTs, the transport mechanisms are Frenkel-Poole and field emission at low and high electric fields respectively. In the case of Au nanorods, the hopping and Frenkel-Poole mechanisms are detected at low and high electric fields respectively. Finally, for vertically aligned CNTs the current-voltage characteristic is found to follow ohm's law. The discharge rate through the bulk material is found to depend on nanofillers morphology.

1. Introduction

RF-MEMS capacitive switches are promising devices for several applications, especially in the field of wireless communications. Their ultra-high linearity, almost zero power consumption, compatibility with silicon technology and the ability to manage signals close to hundreds GHz, make them the most prominent candidate to succeed the conventional semiconductor based switches [1]. In contrary of these attractive benefits, there are reliability issues, among them the most severe is dielectric charging, hindering their commercialization as “component off-the-shelf”. During the devices' operation, specifically during actuation, charges are injected and trapped inside the dielectric causing erratic device behavior, which in most cases may lead to stiction and device failure.

In order to mitigate the dielectric charging significant effort has been paid employing various composition SiNx [2–4]. In all cases the dielectric film has been extensively studied aiming to control its electrical properties considering that beyond the percolation threshold, $x_c = 1.0$, the Si–Si bonds fail to form continuous percolation paths across the network [5]. The intensive study of Si-rich material [6–8] led to better understanding of SiNx electrical properties but still did not provide solution to the persisting problem of dielectric charging.

In a MEMS capacitive switch during up-state the stored charge can only be drained through the bottom electrode, so the ability to quickly remove the injected and trapped charge is essential. In order to enhance this process the first devices with nanostructured dielectric film, with carbon nanotubes (CNTs) embedded in the upper part of the SiNx film was presented by C. Bordas et al. in [9] where they demonstrated that the presence of CNTs improves the device reliability. Considering the effect of percolation and the variable length tunneling taking place in nanostructured dielectrics, their impact on charging mitigation has been discussed in [10].

The present paper aims to investigate, for the first time, the electrical properties of nanostructured SiNx that has been fabricated with different techniques, by embedding (i) CNTs with random orientations, (ii) columnar bunches of aligned CNTs and (iii) columnar Au nanorods. In all cases, the dielectric film has the same thickness and the deposition was performed in two steps of equal thickness where the bottom film was nanostructured. Metal-Insulator-Metal (MIM) capacitors and MEMS capacitive switches were used to assess the effect of dielectric film structure on the electrical properties. The charge transport mechanism was assessed through current - voltage characteristics and the charge draining efficiency through the top electrode potential decay.

2. Experimental data

As already mentioned, MIM capacitors with three different nanostructured dielectrics were fabricated in order to assess dependence of the electrical properties on the material structure. The details of nanostructured dielectric films fabrication is presented below:

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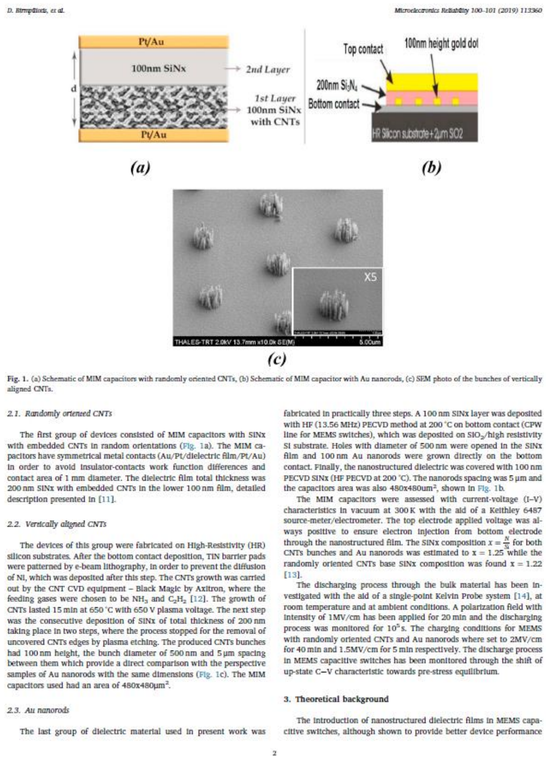





Fig. 1. (a) Schematic of MIM capacitors with randomly oriented CNTs, (b) Schematic of MIM capacitor with Au nanorods, (c) SEM photo of the bunches of vertically aligned CNTs.

2.1. Randomly oriented CNTs

The first group of devices consisted of MIM capacitors with SiNx with embedded CNTs in random orientations (Fig. 1a). The MIM capacitors have symmetrical metal contacts (Au/Pt/dielectric film/Pt/Au) in order to avoid insulator-contacts work function differences and contact area of 1 mm diameter. The dielectric film total thickness was 200 nm SiNx with embedded CNTs in the lower 100 nm film, detailed description presented in [11].

2.2. Vertically aligned CNTs

The devices of this group were fabricated on High-Resistivity (HR) silicon substrates. After the bottom contact deposition, TiN barrier pads were patterned by e-beam lithography, in order to prevent the diffusion of Ni, which was deposited after this step. The CNTs growth was carried out by the CNT CVD equipment – Black Magic by Axitron, where the feeding gases were chosen to be $NH_3$ and $C_2H_2$ [12]. The growth of CNTs lasted 15 min at 650 °C with 650 V plasma voltage. The next step was the consecutive deposition of SiNx of total thickness of 200 nm taking place in two steps, where the process stopped for the removal of uncovered CNTs edges by plasma etching. The produced CNTs bunches had 100 nm height, the bunch diameter of 500 nm and 5 μm spacing between them which provide a direct comparison with the perspective samples of Au nanorods with the same dimensions (Fig. 1c). The MIM capacitors used had an area of 480x480μm².

2.3. Au nanorods

The last group of dielectric material used in present work was fabricated in practically three steps. A 100 nm SiNx layer was deposited with HF (13.56 MHz) PECVD method at 200 °C on bottom contact (CPW line for MEMS switches), which was deposited on $SiO_2$/high resistivity Si substrate. Holes with diameter of 500 nm were opened in the SiNx film and 100 nm Au nanorods were grown directly on the bottom contact. Finally, the nanostructured dielectric was covered with 100 nm PECVD SiNx (HF PECVD at 200 °C). The nanorods spacing was 5 μm and the capacitors area was also 480x480um², shown in Fig. 1b.

The MIM capacitors were assessed with current-voltage (I–V) characteristics in vacuum at 300 K with the aid of a Keithley 6487 source-meter/electrometer. The top electrode applied voltage was always positive to ensure electron injection from bottom electrode through the nanostructured film. The SiNx composition $x = \frac{N}{Si}$ for both CNTs bunches and Au nanorods was estimated to x = 1.25 while the randomly oriented CNTs base SiNx composition was found x = 1.22 [13].

The discharging process through the bulk material has been investigated with the aid of a single-point Kelvin Probe system [14], at room temperature and at ambient conditions. A polarization field with intensity of 1MV/cm has been applied for 20 min and the discharging process was monitored for $10^5$ s. The charging conditions for MEMS with randomly oriented CNTs and Au nanorods where set to 2MV/cm for 40 min and 1.5MV/cm for 5 min respectively. The discharge process in MEMS capacitive switches has been monitored through the shift of up-state C–V characteristic towards pre-stress equilibrium.

3. Theoretical background

The introduction of nanostructured dielectric films in MEMS capacitive switches, although shown to provide better device performance

Ευρωπαϊκή Ένωση
Ευρωπαϊκό Ταμείο Περιφερειακής Ανάπτυξης
ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
ΥΠΟΥΡΓΕΙΟ ΟΙΚΟΝΟΜΙΑΣ & ΑΝΑΠΤΥΞΗΣ
ΕΙΔΙΚΗ ΓΡΑΜΜΑΤΕΙΑ ΕΤΠΑ & ΤΣ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ ΕΠΑνΕΚ
ΕΠΑνΕΚ 2014-2020
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ΑΝΤΑΓΩΝΙΣΤΙΚΟΤΗΤΑ
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ΚΑΙΝΟΤΟΜΙΑ
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ανάπτυξη - εργασία - αλληλεγγύη
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RADAR



[9], has not been studied in depth. As already mentioned, the increase of charge draining through percolation has been discussed in [10] and initial assessment results of field emission in MEMS dielectric films with randomly oriented CNTs were demonstrated in [11,15].

In a nanostructured dielectric the measured current has to consider the basic charge transport mechanisms contributing through parallel paths [16]:

$$J = J_1 + J_2 + J_3 \tag{1}$$

where

$$J_1 = C_1 F \exp\left(-\frac{q\varphi_1}{kT}\right)\exp\left(\frac{qFr}{kT}\right)\exp\left(-\frac{r}{a}\right) \tag{2}$$

$$J_2 = C_2 F \exp\left\{-\frac{q\left[\varphi_2 - \left(\frac{qF}{\pi\varepsilon_0\varepsilon_d}\right)^{\frac{1}{2}}\right]}{kT}\right\} \tag{3}$$

$$J_3 = C_3 F^2 \exp\left(-\frac{E_3}{F}\right) \tag{4}$$

In this model $J_1$ is the hopping mechanism current, $J_2$ the contribution of Poole - Frenkel conduction and $J_3$ the Fowler – Nordheim (F–N) tunneling current, where $C_1$, $C_2$, $C_3$ are constants, $q\varphi_1$, $q\varphi_2$ the barrier height for each mechanism and $\alpha$ a constant that in most cases equals to Bohr radius.

In order to understand the impact of top layer on field emission it is essential to bear in mind that the coating of field emitters with a thin layer of certain wide band gap materials initially enhances emissivity. Increasing the thickness of the wide band gap material beyond a critical point, the emissivity of the coated emitter falls below that of the uncoated emitter [17,18]. Thus, the electrons can escape from the SiNx surface to a vacuum with greater ease than from the pristine CNT surface to a vacuum since the electron affinity of SiNx (−2 eV [19]) is lower than the work function of the CNTs ranging from 4.5 eV [20] to 5 eV [21].

For uncoated nanowires, Y. Chen et al., [17] have demonstrated that field emission may occur in vacuum for different CNT orientations. Extracting the data from Fig. 4 of [17] we present in Fig. 2 the Fowler-Nordheim plot which shows that for the parallel to substrate CNTs the field enhancement factor is larger.

## 4. Results and discussion

In MIM capacitors charge injection takes place under homogenous

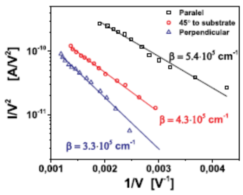


Fig. 2. F–N plot for CNTs for different orientations. Data obtained from Fig. 4 of [17].

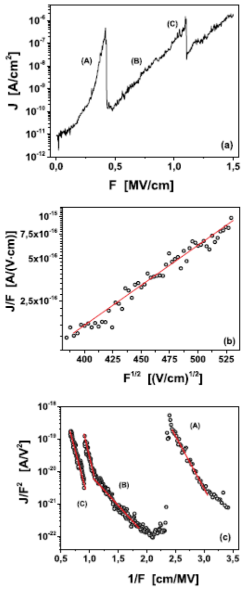


Fig. 3. (a) Ascending J-F characteristic, (b) Poole-Frenkel signature up to 250 kV/cm and (c) F–N plot in the range of 0.35-2MV/cm of the randomly oriented CNTs films.

electric field, generated from the parallel metal electrodes. However, the presence of nanoparticles in the lower half of dielectric films, used in this work, distorts the field homogeneity and the injected charges distribution.

In order to investigate the electrical properties of utilized nanostructured films MIM capacitors the results are separately discussed.





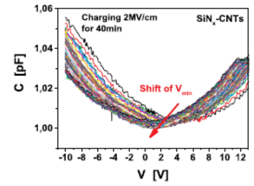


Fig. 4. Shift of $V_{min}$ during discharging of the MEMS switches with randomly oriented CNTs.

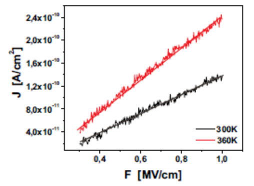


Fig. 5. Current-Voltage characteristic in MIM capacitors with vertically aligned CNT batches for different temperatures.

### 4.1. Assessment of randomly oriented CNTs

#### 4.1.1. MIM capacitors

Fig. 3(a) shows a typical current-voltage characteristic obtained by applying fields up to 1.5MV/cm. The analysis of the ascending branch reveals the presence of field emission process arising from different sources. Particularly, for the ascend branch and for relatively low electric fields, up to 250 kV/cm, the contribution of Poole-Frenkel mechanism appears to be dominant Fig. 3(b). As applied bias increases a transition to field emission is observed, where the measured current increases rapidly Fig. 3(c). The non-continuous behavior of the F–N process has to be attributed to breakdown and CNTs loss [22] followed by contribution from CNTs with different field enhancement factor and emitting effective area.

These results clearly show the simultaneous presence of the two charge transport mechanisms while the hopping that was not detected cannot be excluded.

#### 4.1.2. MEMS capacitive switches

Fig. 4 shows the shift of $V_{min}$ during the discharging process of MEMS capacitive switches with randomly oriented CNTs. Further information about the device structure and experimental details can be found in [15]. In the later work, reference SiNx was compared with the nanostructured one and was found that MEMS switches with embedded randomly oriented CNTs provide faster discharging by an amount of 25%. The reported behavior was directly attributed to the presence of CNTs and the field-emission process, which also takes place during discharging. Furthermore, in the present work it is shown that due to the high electric fields generated by the CNTs the Poole-Frenkel mechanism also arises, thus the contribution of the combined transport mechanisms will provide faster charge draining from the bottom electrode.

### 4.2. Assessment of vertically aligned CNTs

The current-voltage characteristics in these nanostructured dielectrics show a different behavior. Primarily, no field emission is been observed (Fig. 5). The absence or very low field emission can be attributed to the electrostatic screening effect arising from the proximity of neighboring tubes and the large CNTs bunches diameter (500 nm) compared to their uniform length (100 nm) [23]. Calculations have shown that to minimize the screening effect the individual emitters should be evenly separated so that their spacing is greater than their height [24]. Furthermore, considering the fact that the nanotubes are close packed grown in bunches of 500 nm diameter, which corresponds to about 0.8% of the cell of dimension of 5 µm × 5 µm, we arrive to the conclusion that the measured current will arise from two regions, the empty of CNTs area with a field intensity of E and the bunch top area where the field is 2E, behaving like nanorods with properties described in [25].

The current-voltage characteristic (Fig. 5) does not comply with hopping or Frenkel-Poole mechanism. Instead of this, it exhibits a very good agreement with ohms law. Such a behavior although not encountered in silicon-nitride, it may not be excluded for the case of bulk limited conduction [26] in the presence of even a small number of carriers excited in the conduction or valence band. Ohmic like conductivity can be also obtained when hopping conduction occurs with very small hopping distance r although there are no evidences of such condition. Although not observed in the case of random oriented CNTs, this behavior has to be attributed to the presence of the vertically aligned CNTs and the SiNx deposition process. The same behavior is observed at elevated temperature (360 K). The fact that the conductivity increases with temperature leads to the conclusion that the mechanism is thermally activated. Based on these results we are led to the conclusion that further investigation is required for the understanding of transport mechanism and the possible implementation on charging mitigation.

### 4.3. Assessment of Au nanorods

#### 4.3.1. MIM capacitors

As already mentioned above, the presence of nanorods modify the distribution of the electric field intensity at the top interface of the MIM capacitors and the value of ($E_s$) is determined by the height, diameter, spacing of the nanorods and the thickness of the overlaying dielectric film. In [25] a comparison between nanostructured nanorods of different spacing and diameters revealed that the interference of neighboring nanorods is negligible when the spacing extends over an area of about 400–500 nm from the center of each nanorod. This conclusion practically means that for the nanostructured material used in the present work with diameter of 500 nm and 5 µm spacing, the impact of the fringing field will be almost negligible. Hence, the current will be determined by both the local field intensity, the charge injection and the dominant transport mechanisms. Fig. 6 shows a typical current-voltage characteristic for electric fields up to 1MV/cm.

In SiNx the basic transport mechanisms, in absence of any contribution from field emission, are the hopping (Eq. (2)) and Frenkel-Poole (Eq. (3)). The first is usually encountered in low fields regime while the second in high fields regime. In such a dielectric film where the electric field intensity is not uniform, we assumed that Eq. (1)





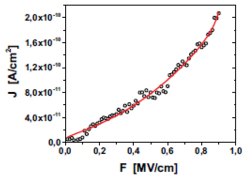


Fig. 6. Current-Voltage characteristic of Au nanorods MIMs. Fitted with the sum of hopping (Eq. (2)) and Poole-Frenkel (Eq. (3)).

contains only two terms and fitted the sum to experimentally obtained I-V characteristic (Fig. 6). Here it must be pointed out that the fitting results cannot be directly used to extract information on material properties but in contrary provides information on the physics on the charge transport processes in such a nanostructured dielectric film.

#### 4.3.2. MEMS capacitive switches

Fig. 7 shows the shift of $V_{min}$ during discharging of the MEMS switches with Au nanorods. In [25], a detailed comparison between the reference SiNx and nanostructured films with Au nanorods of different diameters and spacings revealed that discharging process in MEMS switches is almost 17% faster, a behavior that may attributed to the fact that Poole-Frenkel mechanism arises from relatively low electric field intensities.

### 4.4. Kelvin probe assessment

The decay of surface potential in a charged capacitive MEMS dielectric film and the top electrode in a charged MIM capacitor provide the information on the discharge process of dielectric film when the MEMS bridge is in up-state. In the present work the decay of surface potential is assessed with the aid of a single-point Kelvin Probe system [14], at room temperature and at ambient conditions. The method simulates the discharge process in a MEMS capacitive switch when the bridge can be still restored in the up-state. The results are presented in Fig. 8a for the random oriented CNTs and in Fig. 8b for the vertically

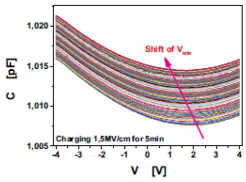


Fig. 7. Shift of $V_{min}$ during discharging of the MEMS switches with Au nanorods.

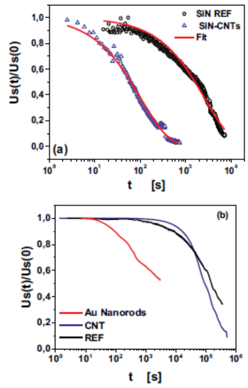


Fig. 8. Normalized surface potential decay with respect to the reference material for (a) randomly oriented CNTs, (b) vertically aligned CNTs and Au nanorods.

aligned CNTs and Au nanorods that occupy only about 0.8% of nanostructure unit cell of 5 µm × 5 µm. The data of the corresponding reference materials are also included in each figure. Finally, the plots were normalized to initial potential in order to facilitate the comparison of the impact of the nanostructured material in the discharge process, which obviously increases the decay rate in these materials.

## 5. Conclusions

The electrical properties of SiNx with embedded CNTs, of random orientation or vertically aligned bunches, and Au nanorods have been investigated. It is found that the electrical properties are significantly affected by both the embedded nanofiller and the orientation. Thus, in the case of random oriented CNTs the transport mechanisms are Frenkel-Poole and field emission at low and high electric fields respectively. In the case of Au nanorods, the hopping and Frenkel-Poole mechanisms are detected at low and high electric fields respectively. Finally, for vertically aligned CNTs the current-voltage characteristic is found to follow ohm's law, leading to the conclusion that this material requires further investigation. The discharge rate through the bulk material is found to increase with the addition of nanofillers. It is important to notice that the discharge rate depends on the host material deposition conditions and the organization of the nanofillers. Furthermore, it is important to notice that for the vertically aligned nanostructures their density plays a crucial role on the discharge process. Moreover, for the vertically aligned bunches of CNTs the screening





effect does not allow the manifestation of field emission and therefore the benefits of isolated CNTs. Considering the thermal stress on Si substrate during CNTs growth and the potential presence of thermal donors in the substrate we are led to the conclusion that all proposed nanostructured materials can be implemented in MEMS with the randomly orientated CNTs representing the lower cost and easy optimization followed by the higher cost Au nanorods reinforced material. The vertically aligned CNT bunches requires rigorous optimization in both the growth temperature and the understanding the resulting material electrical properties.

## Acknowledgements

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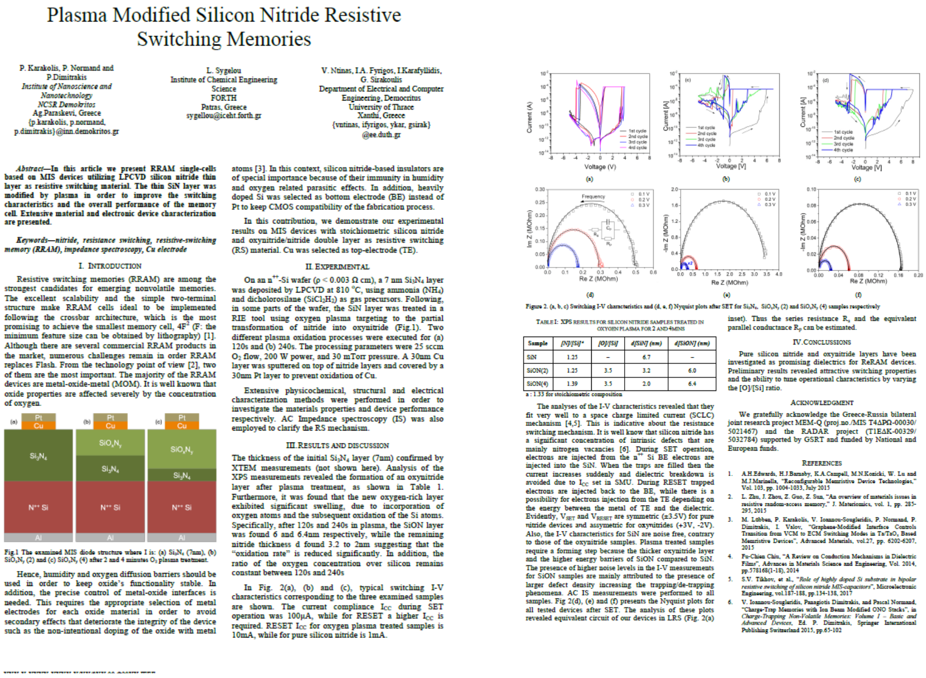
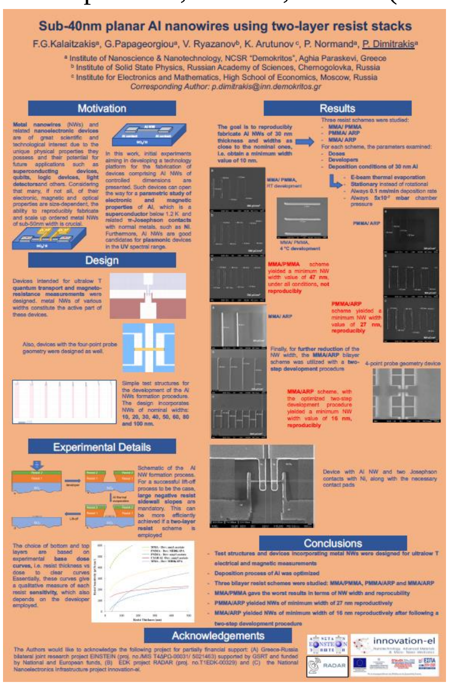
### 3.2. Διεθνή Συνέδρια

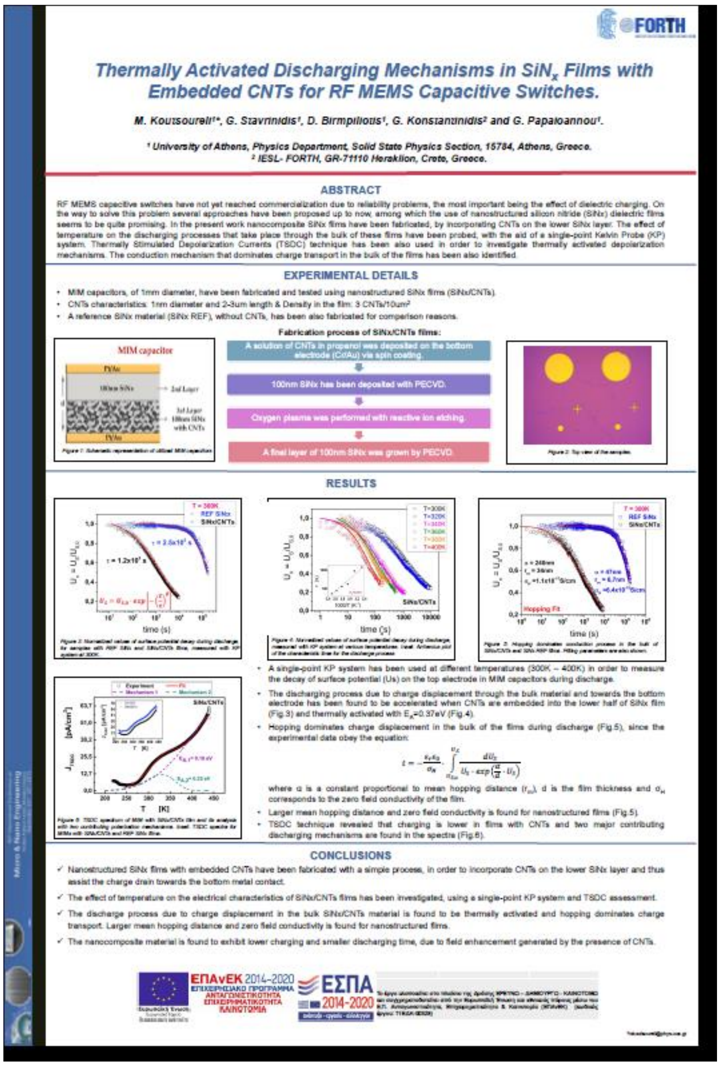
1. P. Dimitrakis, Panagiotis Karakolis, Pascal Normand, Georgios Ch. Sirakoulis and Ioannis Karafyllidis “Plasma Modified Silicon Nitride Resistive Switching Memories”, NANOARCH 2019, 15th ACM/IEEE International Symposium on Nanoscale Architectures, July 15-19 2019, Qingdao, China


Plasma Modified Silicon Nitride Resistive Switching Memories

2. Fotis Kalaitzakis, George Papageorgiou, V. Ryazanov, K. Arutunov, Pascal Normand, Panagiotis Dimitrakis, “Sub40 nm planar Al nanowires using two-layer resist stacks”, 45th International Conference on Micro and Nano Engineering (MNE) 2019, 23-26 September, Rhodes, Greece (Poster Presentation).

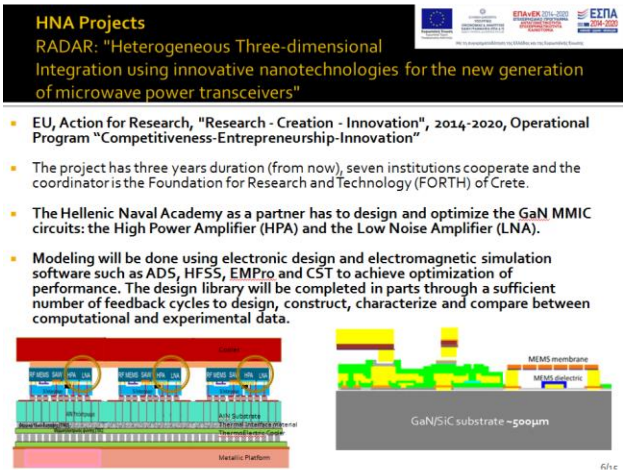


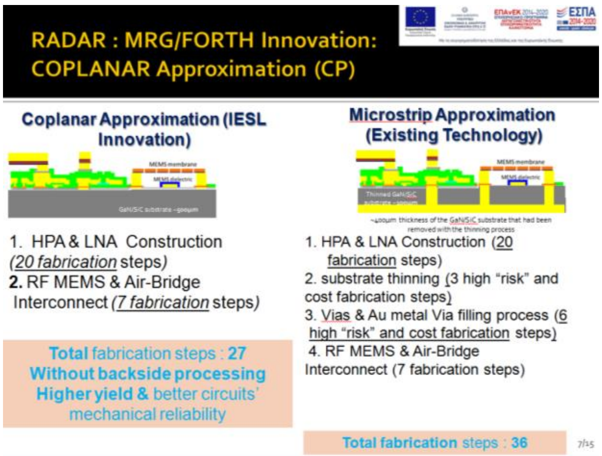
3. Matroni Koutsoureli, George Stavrinidis, Dimitrios Birmpiliotis, George Konstantinidis, George Papaioannou, "Thermally Activated Discharging Mechanisms in SiNx Films with Embedded CNTs for RF MEMS Capacitive Switches" 45$^{th}$ International Conference on Micro& Nano Engeneering, 23-26 September, 2019

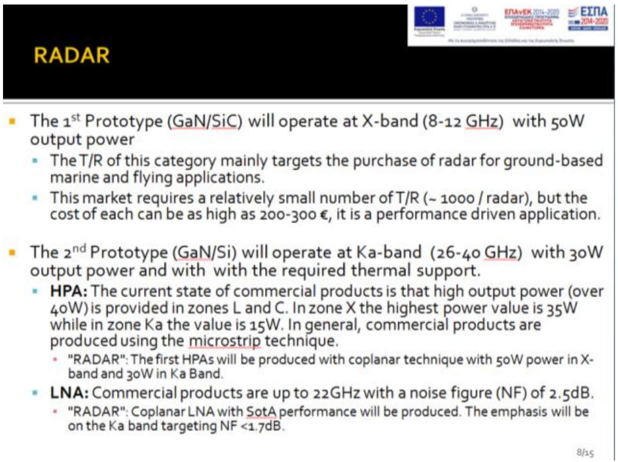


## 4. Παρουσιάσεις σε διεθνείς επιστημονικές συναντήσεις

1. Συμμετοχή στο 40th TCM CapTech Meeting, 17 Σεπτεμβρίου 2018, EDA, Βρυξέλλες, Παρουσίαση του ΡΑΝΤΑΡ

# 5. Προβολή σε Μέσα Κοινωνικής Δικτύωσης και Εταιρικές Ιστοσελίδες

1. Προβολή του έργου και της εξέλιξης του στα Μέσα Κοινωνικής Δικτύωσης.


https://www.prismaelectronics.eu/index.php/en/profil-en/news-en/186-the-radar-project-consortium-held-its-third-plenary-meeting-in-athens