

**Design and Optimization of Organic and 2D materials-
based Field Effect Transistors (FETs) for Gamma
radiation Dosimetry**

SONAM JAIN



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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based Field Effect Transistors (FETs) for Gamma
radiation Dosimetry**

by

SONAM JAIN

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



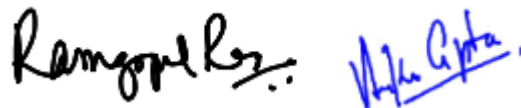
INDIAN INSTITUTE OF TECHNOLOGY DELHI

JANUARY 2021

*Dedicated to
My parents and sister*

Certificate

This is to certify that the thesis entitled “**Design and Optimization of Organic and 2D materials-based Field Effect Transistors (FETs) for Gamma radiation Dosimetry**” being submitted by **Ms. Sonam Jain** for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of bonafide work done by her under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.



Date: 13 Jan'2021
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Abstract

Research and development in the field of microelectronics industry always looks forward for integration of innovative and cost-effective devices and technologies. The field of gamma radiation detection is a continuously growing area of research, due to its vast applications spanning from space radiation, medical diagnostics to the food industry. Ionizing radiation (such as X-rays, gamma rays) is widely used as a source in medical radiotherapy for destroying the tumor cells.

Field-effect transistors can be made from both organic and inorganic semiconductors; differences in performance capabilities vary a lot, though. Inorganic materials suffer from various drawbacks, such as poor mechanical flexibility, inability to cover large areas, unaltered structural integrity/rigidity and poor human-tissue equivalence. Organic semiconductors and Graphene based devices can overcome these drawbacks and make an ideal material for the development of low-cost and scalable dosimeters. Organic materials can be used to cover a larger and flexible surface due to their polymeric backbone. CVD grown graphene on Cu foil can be transferred to large-area surfaces. This makes them superior to inorganic semiconductors in many applications. Organic semiconductor and graphene-based devices undergo mobility degradation, charge trapping and shift in threshold voltage upon irradiation exposure. These radiation effects can be utilized as sensing parameters for direct radiation dosimetry.

For low-cost sensors, we explored the electrical and material properties of TIPS-Pentacene upon irradiation to different gamma doses from cobalt-60 (^{60}Co) radiation source at room temperature. Interface trap/defect generation was studied post gamma irradiation of TIPS-Pentacene transistors. The effect of traps/defects at the bulk/surface of TIPS-Pentacene and SiO_2/Si interface states on the sensing behavior was studied. Further, the role of dielectric and channel materials on radiation sensitivity was studied. A theoretical model was developed to understand the change in ON-current and channel doping. The change in surface potential of the film was studied by Kelvin probe force microscopy (KPFM) to analyze radiation induced effects.

Later, the electrical and material properties of Graphene-based field-effect transistors (GFETs) were studied with various doses of gamma radiation. Graphene-based field-effect

transistors exhibit p-type doping of the Dirac point upon exposure to gamma radiation. Concurrently, an asymmetric degradation in the electron and hole mobility was observed with the former degrading more rapidly. It is shown that change in the Dirac voltage and carrier mobility is strongly dependent on the dose of gamma radiation. The core level changes and the generation of new states in the material band-gap upon exposure to ionizing radiation were studied using X-ray photoelectron spectroscopy (XPS). The change in contact potential difference was estimated through the Kelvin probe force microscopy (KPFM). In addition, a time-dependent room temperature annealing study was also performed on the devices to study the stability of devices. Thus, we propose, that GFET can serve as a real-time dosimeter operating in ambient conditions.

Keywords: OFET, TIPS-Pentacene, graphene, GFET, Ionizing Radiation, Dosimeter, Sensor, XPS, KPFM, Hole doping, GFET performance tuning

माइक्रोइलेक्ट्रॉनिक उद्योग के क्षेत्र में अनुसंधान और विकास हमेशा नवीन और लागत प्रभावी उपकरणों और प्रौद्योगिकियों के एकीकरण के लिए तत्पर हैं। अंतरिक्ष विकिरण, चिकित्सा निदान से लेकर खाद्य उद्योग तक फैले इसके विशाल अनुप्रयोगों के कारण गामा विकिरण का पता लगाने का क्षेत्र निरंतर अनुसंधान का क्षेत्र है। आयनिंग विकिरण (जैसे एक्स-रे, गामा किरणें) व्यापक रूप से ट्यूमर कोशिकाओं को नष्ट करने के लिए चिकित्सा रेडियोथेरेपी में एक स्रोत के रूप में उपयोग किया जाता है।

मॉसफेट ट्रांजिस्टर को कार्बनिक और अकार्बनिक अर्धचालकों दोनों से बनाया जा सकता है; यद्यपि प्रदर्शन क्षमताओं में अंतर बहुत भिन्न होता है। अकार्बनिक सामग्री विभिन्न कमियों से ग्रस्त हैं, जैसे कि खराब यांत्रिक लचीलापन, बड़े क्षेत्रों को कवर करने में असमर्थता, अनचाही संरचनात्मक अखंडता / कठोरता और खराब मानव-उत्तक तुल्यता। कार्बनिक अर्धचालक और ग्राफीन आधारित उपकरण इन कमियों को दूर कर सकते हैं और कम लागत और स्केलेबल डॉसिमिटर के विकास के लिए एक आदर्श सामग्री बना सकते हैं। कार्बनिक पदार्थों का उपयोग उनके बहुलक रीढ़ के कारण एक बड़ी और लचीली सतह को कवर करने के लिए किया जा सकता है। रासायनिक वाष्प जमाव (CVD) का उपयोग करके कॉपर पट्टी पर उगाए गए ग्राफीन को बड़े क्षेत्र की सतहों पर स्थानांतरित किया जा सकता है। यह उन्हें कई अनुप्रयोगों में अकार्बनिक अर्धचालकों से बेहतर बनाता है। ऑर्गेनिक सेमीकंडक्टर और ग्राफीन-आधारित उपकरण गतिशीलता जोखिम से गुजरते हैं, विकिरण के संपर्क में आने पर थ्रेसहोल्ड वोल्टेज में चार्ज और शिफ्ट होते हैं। इन विकिरण प्रभावों को प्रत्यक्ष विकिरण डॉसिमेट्री के लिए संवेदन मापदंडों के रूप में उपयोग किया जा सकता है।

कम लागत वाले सेंसर के लिए, हमने कमरे के तापमान पर कोबाल्ट -60 (^{60}Co) विकिरण स्रोत से विभिन्न गामा खुराक के विकिरण पर TIPS-Pentacene के विद्युत और भौतिक गुणों का पता लगाया। इंटरफ़ेस ट्रैप / डिफेक्ट जनरेशन का अध्ययन TIPS-Pentacene ट्रांजिस्टर के गामा विकिरण के बाद किया गया था। TIPS-Pentacene की सतह पर मौजूद ट्रैप्स/डिफेक्ट्स और SiO_2/Si इंटरफ़ेस स्टेट की थोक / सतह पर जाल / दोष के प्रभाव का सेंसिंग व्यवहार पर अध्ययन किया गया था।

इसके अलावा, डाइइलेक्ट्रिक सामग्री और चैनल सामग्री की भूमिका का विकिरण संवेदनशीलता पर अध्ययन किया गया था। ON-current और चैनल डोपिंग में परिवर्तन को समझने के लिए एक सैद्धांतिक मॉडल विकसित किया गया था। केल्विन जांच बल माइक्रोस्कोपी (KPFM) द्वारा विकिरण प्रेरित प्रभावों का विश्लेषण करने के लिए फिल्म की सतह की क्षमता में परिवर्तन का अध्ययन किया गया था। बाद में, ग्राफीन आधारित MOS ट्रांजिस्टर (जीएफईटी) के विद्युत और भौतिक गुणों को गामा विकिरण की विभिन्न खुराक के साथ अध्ययन किया गया था। ग्राफीन आधारित MOS ट्रांजिस्टर गामा विकिरण के संपर्क में डीरेक बिंदु के पी-टाइप डोपिंग का प्रदर्शन करते हैं। समवर्ती रूप से, इलेक्ट्रॉन और होल की गतिशीलता में एक असममित गिरावट पूर्व में अधिक तेजी के साथ देखी गई थी।

हमने यह दिखाया है कि डिराक वोल्टेज और वाहक गतिशीलता में परिवर्तन गामा विकिरण की खुराक पर दृढ़ता से निर्भर है। आयनिंग विकिरण के संपर्क में आने वाले भौतिक बैंड-गैप में कोर स्तर में बदलाव और नए स्टेट का अध्ययन एक्स-रे फोटोइलेक्ट्रॉन स्पेक्ट्रोस्कोपी (एक्सपीएस) का उपयोग करके किया गया था। केल्विन जांच बल माइक्रोस्कोपी (KPFM) के माध्यम से संपर्क संभावित अंतर में परिवर्तन का अनुमान लगाया गया था। इसके अलावा, उपकरणों की स्थिरता का अध्ययन करने के लिए उपकरणों पर एक समय-निर्भर कमरे के तापमान का अध्ययन भी किया गया था। इस प्रकार, हम प्रस्ताव करते हैं,

कि GFET डिवाइस एक निष्क्रिय डॉसिमिटर के रूप में काम कर सकता है जो परिवेशीय परिस्थितियों में काम कर सकता है।

कीवर्ड: OFET, TIPS-Pentacene, graphene, GFET, आयनित विकिरण, डोसमीटर, सेंसर, XPS, केल्विन जांच बल माइक्रोस्कोपी (KPFM), होल डोपिंग, GFET प्रदर्शन ट्यूनिंग

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List of Symbols

MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
I_{OFF}	Drain current at zero gate voltage
I_{ON}	Drain current at gate voltage equal to supply voltage
V_{DD}	Supply Voltage
t_{ox}	Gate Oxide Thickness
V_{DS}	Drain -to- Source Voltage
V_{GS}	Gate -to- Source Voltage
V_{TH}	Threshold Voltage
V_{DP}	Dirac point Voltage
μ	Mobility
g_m	Transconductance
C_{ox}	oxide capacitance
SS	Subthreshold Swing
Dit	Interface Trap density
V_{CPD}	contact potential difference
ϕ_{sample}	Sample Work Function
ϕ_{tip}	Tip Work Function
I_{D}	Intensity of D band
$I_{2\text{D}}$	Intensity of 2D band
I_{G}	Intensity of G band
FWHM	Full width half maximum
N_{D}	Point defect density
n_{trap}	Interface trap density