Accelerated Fabrication of Customized Nanoscale Interfaces using Focused Beam-Induced Direct-Write Nanopatterning

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Abstract: A novel rapid prototyping approach for bottom-up nanostructure circuits is presented, leveraging a hybrid metal deposition and patterning technique that combines focused ion and electron beam-induced decomposition of a metal-organic precursor gas. Ohmic contacts are established via electron beam deposition, followed by ion beam deposition for expedited interconnect formation. The versatility of this method is showcased through two distinct applications: (1) three-terminal transport measurements of Y-junction carbon nanotubes, and (2) fabrication of nanocircuits for assessing electromechanical degradation in silver nanowires.

Keywords: focused beam nanopatterning, direct-write nanofabrication, customized nanoscale interfaces, accelerated fabrication, nanotechnology, materials science, nanoengineering

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1. Introduction

Rapid prototyping of nanostructure circuits is crucial for advancing nanotechnology research. Traditional methods, such as electron beam lithography, are time-consuming and often result in poor yield. A novel approach using combined electron and ion beam-induced deposition offers a promising solution, enabling rapid and accurate electrical testing of one-dimensional nanostructures, such as nanowires and nanotubes. This technique has the potential to revolutionize nanoelectronics, nanosensing, and nanophotonics by enabling the rapid fabrication of complex nanostructure circuits with high precision and flexibility [1–3].

The development of techniques for rapid and accurate electrical testing of one-dimensional (1D) nanostructures, such as nanowires and nanotubes, is crucial for advancing nanotechnology research. These nanostructures have shown great promise for applications in electronics, photonics, and sensors, but their electrical properties must be thoroughly characterized in order to realize their full potential. Traditional methods for fabricating prototypical nanocircuits, such as electron beam lithography, are often time-consuming and result in poor yield, hindering the rapid progress of nanotechnology research [3,4]. Recently, a novel approach using combined electron and ion beam-induced deposition has emerged as a promising solution, enabling rapid prototyping of complex nanostructure circuits with high precision and flexibility. This technique has the potential to revolutionize nanoelectronics, nanosensing, and nanophotonics by enabling the rapid fabrication and testing of 1D nanostructures, and is the focus of this article.

The rapid advancement of nanotechnology relies heavily on the development of techniques for rapid and accurate electrical testing of one-dimensional (1D) nanostructures, such as nanowires and nanotubes. These nanostructures have shown immense promise for applications in electronics, photonics, and sensors, due to their unique electrical, optical, and mechanical properties. However, their electrical properties must be thoroughly characterized in order to realize their full potential and integrate them into functional devices. Traditional methods for fabricating prototypical nanocircuits, such as electron beam lithography, are often time-consuming, complex, and result in poor yield, hindering the rapid progress of nanotechnology research. The need for a more efficient and effective approach has led to the exploration of novel techniques, such as direct-write nanopatterning by electron and ion beam-induced deposition. This technique has emerged as a promising solution, enabling rapid prototyping of complex nanostructure circuits with high precision and flexibility. By leveraging the advantages of electron and ion beam-induced deposition, researchers can now fabricate and test 1D nanostructures with unprecedented speed and accuracy, paving the way for breakthroughs in nanoelectronics, nanosensing, and nanophotonics [3–5]. This article delves into the details of this innovative approach and its applications in advancing nanotechnology research.

The rapid advancement of nanotechnology is contingent upon the development of innovative techniques for rapid and accurate electrical testing of one-dimensional (1D) nanostructures, such as nanowires and nanotubes. These nanostructures have garnered significant attention in recent years due to their unique electrical, optical, and mechanical properties, which make them ideal candidates for applications in electronics, photonics, and sensors. However, the realization of their full potential is hindered by the limitations of traditional methods for fabricating prototypical nanocircuits, such as electron beam lithography. These methods are often time-consuming, complex, and result in poor yield, thereby hindering the rapid progress of nanotechnology research [1,4]. The need for a more efficient and effective approach has led to the exploration of novel techniques, such as direct-write nanopatterning by electron and ion beam-induced deposition. This technique has emerged as a promising solution, enabling rapid prototyping of complex nanostructure circuits with high precision and flexibility. By leveraging the advantages of electron and ion beam-induced deposition, researchers can now fabricate and test 1D nanostructures with unprecedented speed and accuracy, paving the way for breakthroughs in nanoelectronics, nanosensing, and nanophotonics. The ability to rapidly prototype and test nanostructure circuits is crucial for advancing our understanding of the electrical properties of 1D nanostructures and for the development of functional devices. This article provides a comprehensive overview of this innovative approach, highlighting its advantages, applications, and potential impact on the field of nanotechnology.

2. Experimental Procedure

Sample preparation is a critical step in the experimental procedure. The samples of 1D nanostructures, such as nanowires or nanotubes, are first prepared on a substrate. The substrate is typically a silicon wafer or a glass slide. The nanostructures are then cleaned using standard procedures to remove any contaminants. This is done to ensure that the surface of the nanostructures is free from any impurities that may affect the deposition process.

Electron beam deposition is a key step in the experimental procedure. The sample is loaded into an FEI Strata 235 M dual beam (FIB/SEM) system, which is equipped with an electron beam source. The electron beam energy is set to 10 keV and the beam current is set to 2 nA. A metal-organic precursor, such as trimethylcyclopentadienyl-platinum, is then heated to 40 °C and injected into the path of the scanning electron beam using a 0.7 mm diameter needle. The precursor is vaporized and deposited onto the sample, forming a Pt line connecting photolithographically pre-patterned Au electrodes on oxidized Si substrates. The beam raster dimensions are set to 40 μm in length and 250 nm in width.

Ion beam deposition is another critical step in the experimental procedure. The sample is still loaded in the FEI Strata 235 M dual beam (FIB/SEM) system, but now the ion beam source is used. The ion beam energy is set to 30 keV and the beam current is set to 30 pA. Ga+ ions are used and the pixel dwell time is set to 0.4 μs with no overlap between pixels. The same precursor and beam raster dimensions as in step 2 are used to deposit Pt lines.

Characterization is an essential step in the experimental procedure. The resistivity of the deposited Pt lines is measured using four-point probe measurements. This is done to determine the electrical properties of the deposited material. In-situ TEM imaging is also performed to study the structure and stability of the deposited material. Additionally, the leakage current between closely spaced Pt lines is measured to characterize metal delocalization.

The final step in the experimental procedure is to demonstrate the applications of the deposited material. Two applications are demonstrated: three-terminal transport measurements of Y-junction carbon nanotubes and fabrication of contacts and interconnects to metallic nanowires on thin electron-transparent membranes for in-situ TEM imaging of electromechanical degradation. These applications showcase the potential of the deposited material for use in nanoelectronics, nanosensing, and nanophotonics.

3. Results and Discussion

The results of the experiment show that ion beam deposition is superior to electron beam deposition for fabricating nanocircuits due to its superior conductivity and leakage characteristics. However, ion beam deposition cannot be used to make contacts to 1D nanostructures because it would destroy them. Therefore, a two-step process was adopted, where electron beam deposited Pt was used to make contacts to the nanostructures, and then interconnected to prepatterned electrodes using ion beam deposition [3].

The utility of this approach is demonstrated with two examples. The first example is the fabrication of three-terminal contacts to Y-junction carbon nanotubes, which are three-terminal nanostructures with a branching point. The results show that a gate voltage can be used to regulate the channel current. The second example is the study of electromechanical degradation of silver nanowires using in-situ biasing in a TEM [4]. The results show that the nanowires degrade chiefly by resistive heat-induced melting, and that a carbonaceous sheath surrounding the nanowire continues to conduct current after the Ag core has melted.

The discussion highlights the advantages of the two-step process, including the ability to fabricate site-specific contacts to 1D nanostructures and the potential for rapid fabrication of nanocircuits. The limitations of the technique, such as contact resistance effects, are also discussed. Overall, the results demonstrate the potential of direct-write FIB-based lithography for enabling a wide variety of electrical transport investigations in nanotechnology research [5].

The results of the two-terminal transport measurements on the Y-junction nanotube show that the branch connecting terminals 2-3 is three orders of magnitude more conductive than the branch connecting terminals 1-2. This is consistent with the expected behavior of a Y-junction nanotube, where the branching point creates a region of high conductivity. The three-terminal transport measurements on the Y-junction nanotube show that a gate voltage applied to terminal 3 can regulate the channel current between terminals 1 and 2. This is a manifestation of Kirchhoff's law of nodes at the nanoscale. The results also show that the nanotube is metallic in nature, with no rectifying behavior observed [6].

The study of electromechanical degradation of silver nanowires using in-situ biasing in a TEM shows that the nanowires degrade chiefly by resistive heat-induced melting. The results also show that a carbonaceous sheath surrounding the nanowire continues to conduct current after the Ag core has melted. This suggests that the melted Ag is partially incorporated into the sheath, allowing it to continue conducting current [7].

The use of direct-write FIB-based lithography for fabricating site-specific contacts to 1D nanostructures offers several advantages over traditional EBL techniques. These include the ability to fabricate contacts in a rapid and reproducible manner, without the need for resist spin coating or development. Additionally, the technique allows for the fabrication of contacts to nanostructures on thin electron-transparent membranes, which would be difficult or impossible to achieve with traditional EBL techniques [8]. Overall, the results demonstrate the potential of direct-write FIB-based lithography for enabling a wide variety of electrical transport investigations in nanotechnology research. The technique offers a powerful tool for fabricating site-specific contacts to 1D nanostructures, and for studying their electrical properties in a rapid and reproducible manner.

4. Conclusion

In conclusion, this study demonstrates the successful development of a direct-write FIB-based lithography technique for fabricating site-specific contacts to 1D nanostructures. The technique offers a rapid and reproducible method for fabricating contacts to nanostructures, without the need for resist spin coating or development. The use of a two-step process, combining electron beam deposited Pt with ion beam deposition, allows for the fabrication of high-quality contacts with superior conductivity and leakage characteristics. The technique has been successfully applied to the fabrication of three-terminal contacts to Y-junction carbon nanotubes, and to the study of electromechanical degradation of silver nanowires using in-situ biasing in a TEM. The results demonstrate the potential of direct-write FIB-based lithography for enabling a wide variety of electrical transport investigations in nanotechnology research.

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