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Numerical analysis of diameter dependency of control coefficient of carbon nanotube field effect transistor

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Original Research

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Abstract:

This study examines the behavior of carbon nanotube field effect transistors under ballistic conditions by analyzing the effect of gate (α_G) and drain (α_D) control coefficient modifications on the device's diameter. The effect of α_G and α_D on the outcome of carbon nanotube field effect transistors (CNTFETs) has been thoroughly investigated, and the performance of the device has been evaluated using a variety of parameters for different diameters. In this CNTFET design, the lowest sub-threshold swing recorded is 60.7 mV/decade when using a lower CNT diameter which is 1 nm. The smaller value of sub-threshold swing is contributed by the highest value of gate control coefficient i.e. 0.98, which is desirable for a better ratio between the on- and off-currents and faster-switching device. Again, the maximum quantum capacitance obtained was 1.97×10^{-10} F/cm^2, utilizing a smaller CNT diameter of 1 nm. The maximum value of quantum capacitance is supplied by the value of the gate control coefficient, which is 0.83. Also, the highest transconductance measured, with a greater CNT diameter of 5 nm, is 14.50 uS. With a gate control coefficient of 0.98, the quantum capacitance reaches its maximum value. Overall, the sub-threshold swing decreases as the gate control coefficient increases, while it increases as the drain control coefficient increases. Again, as the gate control coefficient increases, the value of quantum capacitance decreases with a smaller diameter, whereas the quantum capacitance of the device does not fluctuate significantly with a larger diameter. When the diameter changes, the drain control coefficient undergoes an analogous transformation. Furthermore, an increase in the gate control coefficient causes the transconductance to increase. However, when the drain control coefficient is increased along with a change in diameter, the transconductance value remains almost unchanged. Thus, the ideal values for both control coefficients can be determined in this manner to ensure optimal performance.

Keywords: Gate control coefficients; Drain control coefficients; Ballistic; Sub-threshold swing; Transconductance; Quantum capacitance

1. Introduction

The problems that arise when silicon-based devices become smaller and smaller are becoming insurmountable. As a result, scientists are looking at potential replacements for silicon technology that will allow for further scalability of transistors. The promise of carbon nanotubes (CNTs), a material discovered in 1991, to solve scaling problems has attracted a lot of interest [1]. The CNT field-effect transistor (CNTFET) was developed due to studies of CNTs' optical and quasi-ideal electrical characteristics, and it has a much lower leakage current than traditional MOSFETs [2, 3]. This is especially helpful for CMOS technology, which operates with a low supply voltage and minimal switching energy and needs an appropriate on-state-to-off-state current ratio. CNTs' modest size and inherent behavior provide a significant benefit (Fig. 1). In addition, leakage current limits how small MOSFET devices may go; hence, their scaling is limited to no less than 10 nm. Compared to MOSFETs, CNTFETs perform better in terms of channel density, on-current state, and oxide-to-channel interface difficulties [4, 5]. Carbon nanotube (CNT) transistors have a ballistic character when their channel length is less than the carrier mean free path (MFP) but longer than the Coulomb blockade length. Nanotubes display a variety of exceptional electrical and mechanical properties because of the unusual resilience of the C-C bond, the tiny atomic diameter of each carbon atom, and the abundance of free k-electrons within their graphitic configuration [6]. These factors contribute to the nanotubes' overall structure. Since drain voltage drops with decreasing CNT diameter, the output current decreases [7]. The control coefficients of the drain (α_G) and the gate (α_G) serve a purpose in the modeling of CNTFETs that mimic MOSFETs (Fig. 2). This is due to the fact that the impacts of both the control coefficient and the diameter change are being investigated. The purpose of this investigation is to determine how carbon nanotube field-effect transistors' control coefficients change different parameters with changing diameters. This work also examines the sub-threshold (SS) and transconductance (gm) for varying diameters, as well as the impacts of gate control coefficients and drain control coefficients on quantum capacitance (C_Q).

2. CNTFET'S simulation modelling

The functioning of MOSFETs in the ballistic domain has been investigated using both fundamental analytical models [8–11] and in-depth computational simulations [11–13]. This work takes into consideration the numerical simulation technique to calculate the mobile charge, the non-equilibrium charge density, and the overall charge formed on the nanotube channel [8, 14, 15]. This investigation aims to assess the efficacy of CNTFET. Within the scope of this inquiry, a capacitance model is used to consider the electrostatics of a CNTFET. In this investigation, we make use of MATLAB to model and simulate the transistor's ballistic transport.

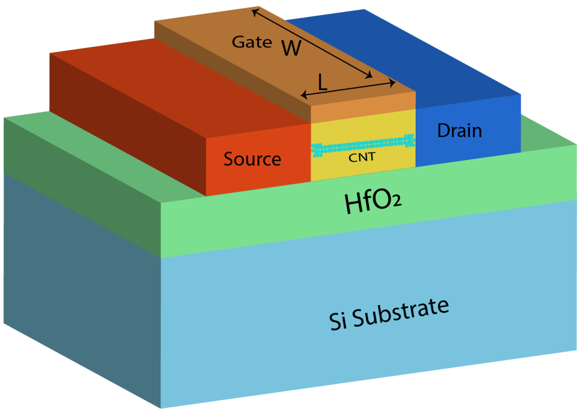

Figure 1. Proposed CNTFET model.

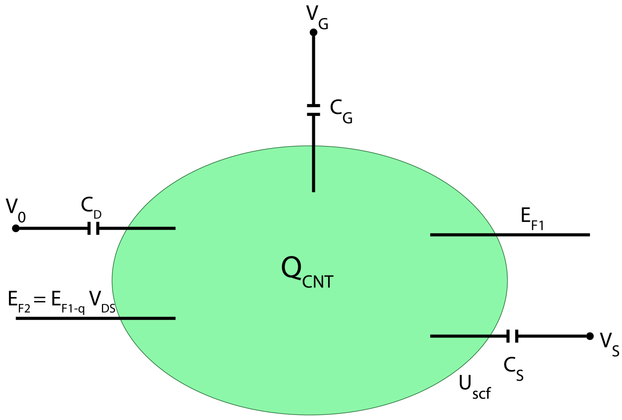

Figure 2. Proposed 2D capacitor model of CNTFET.

The determination of current and voltage characteristics begins once the mobile charge and non-equilibrium charge density have been estimated. The next step is to calculate the current-voltage characteristics. The drain-to-source current at any drain and gate voltage is determined by the first sub-band charge variation resulting from nanotube diameter variations. Both can be found in the model's coefficients. In this work, sub-threshold (SS), transconductance (g_m), and quantum capacitance (C_Q) are examined about gate control coefficients and drain control coefficients [15–17]. The equation of drain to source current

$$I_{DS} = \frac{2qkT}{\pi\hbar}\left[\log\left(1+e^{\left(\frac{U_{SF}}{kT}\right)}\right) - \log\left(1+e^{\left(\frac{U_{DF}}{kT}\right)}\right)\right] \tag{1}$$

where,

$$U_{SF} = E_{f1} - U_{scf} \;\&\; U_{DF} = E_{f2} - U_{scf} \tag{2}$$

Assume the reference Fermi level,

$$E_{F1} = E_F, \;\; E_{F2} = E_F - qV_{DS} \tag{3}$$

The summation of Laplace potential (U_L) at the barrier top evaluates self-consistent potential due to three terminal bias voltages and mobile charge depended potential (U_P).

$$U_{scf} = U_L + U_P \tag{4}$$

$$U_L = -q\left(\alpha_G V_G + \alpha_D V_D + \alpha_S V_S\right) \tag{5}$$

where, α_G, α_D and α_S represent the gate, drain, and source control coefficients respectively.

$$\alpha_G = \frac{c_G}{c_{Sum}} \; \alpha_D = \frac{c_D}{c_{Sum}} \; \alpha_S = \frac{c_S}{c_{Sum}} \tag{6}$$

$$U_P = \frac{q^2}{c_{sum}}\left(N_S + N_D - N_0\right) \tag{7}$$

Here, charge density added by applied voltages,

$$\Delta N = \left(N_S + N_D - N_0\right) \tag{8}$$

$$C_{Sum} = C_G + C_D + C_S \tag{9}$$

where C_G, C_D and C_S are the electrostatic capacitances related to the gate, drain, and source respectively.
The ratio of the individual terminal capacitance to the sum of the terminal capacitances can be used to compute the control coefficient.

3. Result and discussion

The simulation process assumes that the zigzag nanotubes have a chirality of (13, 0), a bandgap of 0.83 eV, and the source Fermi level in the simulation is −0.32 eV. These values may be found in the table below. By modifying the control coefficients, the effect of several factors on the efficacy of CNTFETs was investigated, with the diameter being one of the variables altered.

A high-k dielectric material was selected to be used as gate oxide for the simulation technique that was carried out. The value of the dielectric constant for hafnium oxide (HfO_2) was simulated to be 25, as seen in [16, 18]. Here, the effectiveness of the device was imitated by subjecting it to a 5 nm diameter, which is significantly larger than the typical 1 nm diameter. It is also investigated what happens to the performance of the transistor if the gate control coefficient is changed from 0.83 to 0.98 and the drain control coefficient is changed from 0.05 to 0.30.

3.1 Dependence of sub-threshold swing on the control coefficients

Subthreshold swing is a semiconductor device figure of merit. This merit figure describes the various causes of device deterioration. The subthreshold swing is the gate voltage required to shift the drain current by one order of magnitude [19].

CMOS chips consume a lot of power in sleep mode due to subthreshold leakage. MOSFETs thermally emit carriers across a channel barrier; hence, the SS limit is ln (10) × K_BT/q (60 mV/dec at 300 K). CNTFETs also need this factor. Sub-threshold swing is denoted by [20], Figure 3 depicts the relationship between gate control coefficient (α_G) and sub-threshold swing (SS) diameter variation for nanotubes with thickness and temperature of 1 nm and 300 k, respectively.

$$\text{SS} = \frac{dV_g}{d(\log I_{DS})} = In(10)\frac{KT}{q}(1+\frac{c_d}{c_{ox}}) \tag{10}$$

The oxide layer is composed of hafnium gate oxide. As the graph shows, the sub-threshold swing value decreases as the gate control coefficient increases. For a 1 nm diameter, the SS value for the control coefficient of the gate (α_G) = 0.83 is approximately 71.8 mV/decade. The sub-threshold value does not vary with the diameter. As the value of the gate control coefficient increases, the sub-threshold swing value decreases; at α_G = 0.98, the sub-threshold swing value diminishes to approximately 60.7 mV/decade. Similarly, the sub-threshold swing values for 3 nm and 5 nm diameters remain the same. For optimum CNTFET efficacy, the sub-threshold swing value should be as small as possible. To achieve a higher level of efficacy, it is preferable to employ CNTFET at a smaller diameter. Figure 4 illustrates the drain control coefficient (α_D) versus sub-threshold swing (SS) diameter variation for nanotubes with a thickness of 1 nm and a temperature of 300 k. The oxide layer is composed of hafnium gate oxide. As seen in the graph, as the drain control coefficient (α_D) increases, so does the sub-threshold swing value. Therefore, the larger the diameter, the smaller the SS. The SS value of the drain control coefficient (α_D) = 0.05 is approximately 67.75 mV/decade for a 1 nm diameter. At α_D = 0.30, the SS value is approximately 74.4 mV/decade. Similarly, the sub-threshold variation corresponding to the drain control coefficient (α_D) = 0.05 for a 5 nm diameter is approximately 67.75 mV/decade. When the magnitude of the outflow control coefficient increases, the sub-threshold swing continues to rise. At α_D = 0.30, the sub-threshold swing value increases to approximately 72.8 mV/decade.

3.2 Dependence of quantum capacitance on the control coefficients

Quantum capacitance is a term that refers to the qualities of the material that is used for the channel. When there is a surge in the total amount of charge that is held within the quantum well, the Fermi level is needed to rise higher than the conduction band's edge.

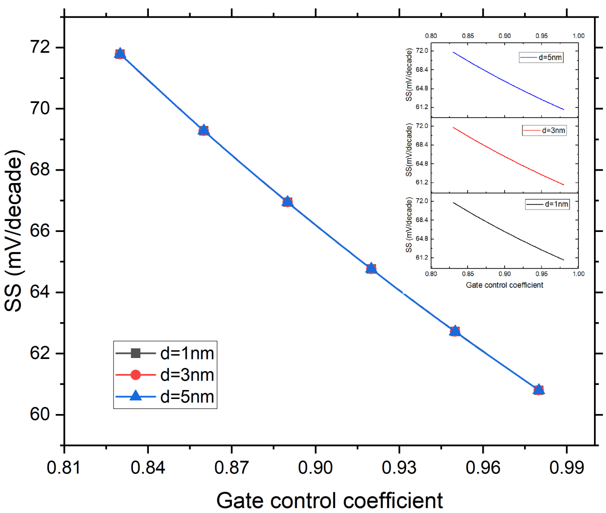

Figure 3. Gate control coefficient (α_G) vs sub-threshold swing.

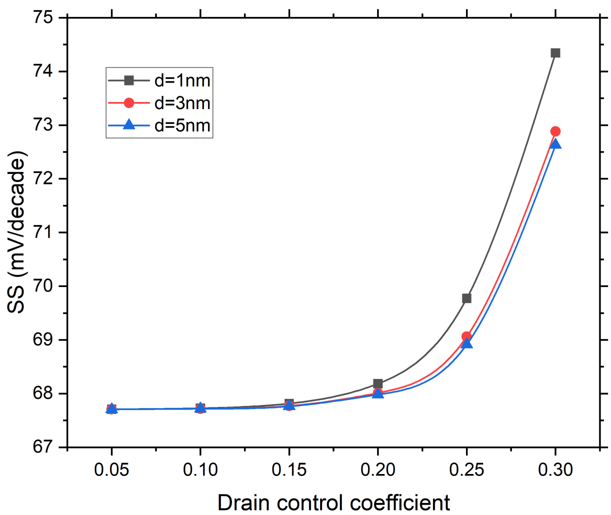

Figure 4. Drain control coefficient (α_D) vs sub-threshold swing.

This is due to the density of states in a semiconductor quantum well being restricted, thus when there is a rise in the total amount of charge that is held within the quantum well. This energy is lost due to the mobility of the Fermi level, which has a direct influence on the idea of quantum capacitance [21]. The equation that states the quantum capacitance is [22]

$$C_Q = \frac{\frac{d(Q)}{dV_G}}{1 - \frac{1}{c_G}\frac{d(Q)}{dV_G}} \tag{11}$$

Figure 5 demonstrates the connection between gate control coefficient (α_G) and quantum capacitance (C_Q) diameter variation for 1 nm thickness and 300 k temperature nanotubes. Hafnium gate oxide makes up the oxide layer. The quantum capacitance value falls as the gate control coefficient rises, as seen in the graph. Furthermore, when the diameter increases, the value of quantum capacitance decreases. The quantum capacitance value for $\alpha_G = 0.83$ for a 1 nm diameter is about 1.97×10^{-10} F/cm^2. The quantum capacitance value collapses as the gate control coefficient value rises; when $\alpha_G = 0.98$, the quantum capacitance value is roughly 1.85×10^{-10} F/cm^2. The quantum capacitance values for 3 nm and 5 nm diameters also fluctuate with α_G. According to the mentioned before Equation (2), the diameter is inversely proportional to the quantum capacitance of CNTFET [22]. Consequently, as the diameter increases, the quantum capacitance decreases.

Figure 6 illustrates the relationship between the drain control coefficient, denoted by α_D, and the quantum capacitance diameter variation, denoted by C_Q, for nanotubes with a thickness of 1 nm and a temperature of 300 k. As can be seen in the graph, the value of C_Q decreases as the drain control coefficient increases from 0.05 to 0.30. In addition to this, a drop in the value of the quantum capacitance may be seen as the diameter grows. 1.91×10^{-10} F/cm^2 is approximately the value for the quantum capacitance when the drain control coefficient is set to 0.05 and the diameter is 1 nm. The value of the quantum capacitance decreases as the value of the drain control coefficient increases; when $\alpha_D = 0.30$, the value of the quantum capacitance is around 1.76×10^{-10} F/cm^2. Furthermore, the value of the quantum capacitance at a diameter of 5 nm is 1.62×10^{-10} F/cm^2 when $\alpha_D = 0.05$, and it is about 1.61×10^{-10} F/cm^2 when $\alpha_D = 0.30$. This indicates that as the diameter increases, the change in α_D does not have as much of an effect on the performance of the CNTFET.

3.3 Dependence of transconductance on the control coefficients

Figure 7 exhibits the diameter-dependent variability of the gate control coefficient (α_G) about the transconductance (g_m). As the diameter of CNTFET changes, the transconductance fluctuates visibly. The conductance of CNTFETs increases linearly with α_G. This causes a large ON-state current and a steady leakage current. Figure 7 depicts slight fluctuations in transconductance value because of the α_G for varied diameters. The transconductance value is derived from the gradient of maximal gate bias voltage and drain bias voltage, as well as the current value. With a diameter of 1 nm and a gate control coefficient of $\alpha_G = 0.83$, the value of transconductance is approximately 11.30 uS; however, this value increases to 13.10 uS with a gate control coefficient of $\alpha_G = 0.98$. Again, at a 5 nm diameter, the value of transconductance is approximately 12.50 uS for a gate control coefficient of $\alpha_G = 0.83$, and the value increases to approximately 14.50 uS for a gate control coefficient of $\alpha_G = 0.98$. Therefore, it can be inferred that there are substantial transconductance impacts in the CNTFET as the diameter increases.

Figure 8 shows the impact of various diameter ranges on the connection between the drain control coefficient (α_D) and the transconductance (g_m). With rising levels of α_D, CNTFETs maintain a nearly constant conductance linearly. However, the transconductance value increases with the increasing diameter. Transconductance is about 12.05 uS for a drain control coefficient (α_D) of 0.05 and increases

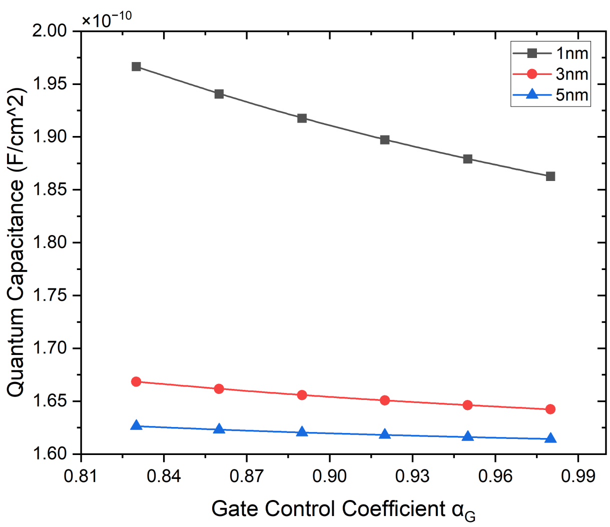

Figure 5. Gate control coefficient (α_G) vs quantum capacitance.

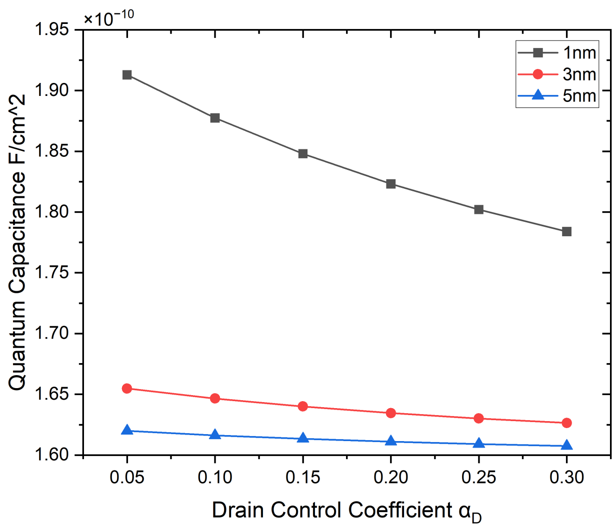

Figure 6. Drain control coefficient (α_D) vs quantum capacitance.

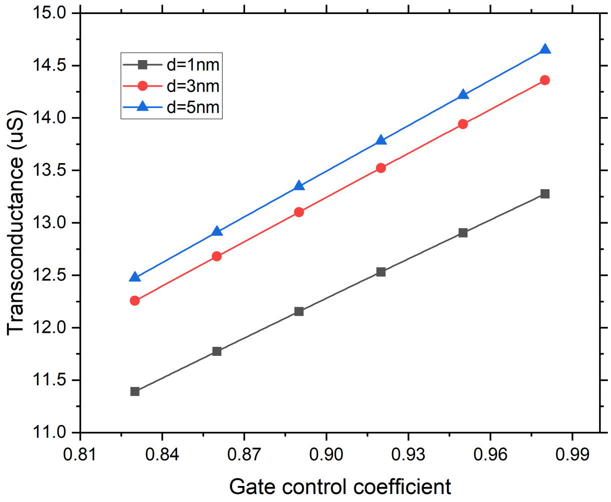

Figure 7. Gate control coefficient (α_G) vs transconductance.

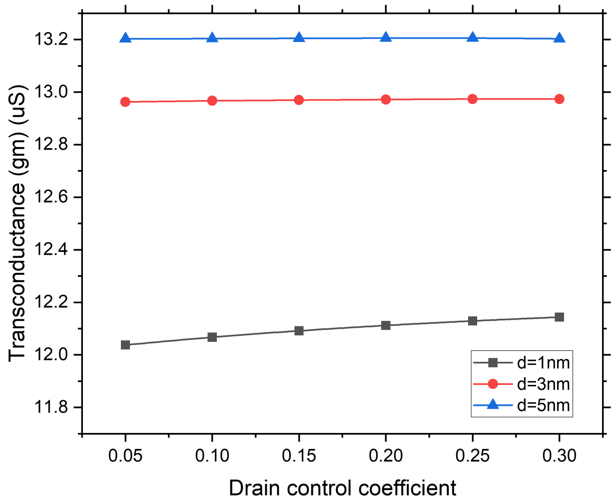

Figure 8. Drain control coefficient (α_D) vs transconductance.

to approximately 12.10 uS with a drain control coefficient (α_D) of 0.30, for a 1 nm diameter. Again, for drain control coefficients of 0.05 and 0.30, the transconductance is around 13.20 uS and almost about the same, respectively. It implies that the transconductance of a CNTFET stays practically constant as the magnitude of the drain control coefficient rises, even as the diameter expands.

In the following research work, we obtained various conclusions from the performance analysis of CNTFET concerning diameter with the variation of gate and drain control coefficients. In comparison to previous research, with the increase in diameter, the value of sub-threshold swing almost remains constant [23]. From the simulation performed in this research work, it can be stated that with the change of diameter, the sub-threshold swing almost remains the same for the gate control coefficient. As a result, the current ratio (I_{ON}/I_{OFF}) remains almost constant. However, the value for sub-threshold swing slightly increases with the increase of drain control coefficient which follows the pattern of the article [24] simulated in SILVACO ATLAS software. In the case of quantum capacitance, a comparison is made with the article [25] where it can be observed that, with the increment of diameter the value for quantum capacitance decreases. In this research, the result findings for quantum capacitance obey the exact pattern respective to both the control coefficients. Again, for transconductance simulation result from the article [26] shows with the increase of diameter values the transconductance also increases. As per this research, the exact output is obtained i.e., with the increase of diameter, the transconductance of CNTFET also increases for both control coefficients.

4. Conclusion

This study presents the results of a comprehensive investigation into the sub-threshold swing, quantum capacitance, and transconductance of a ballistic CNTFET across various levels of diameter. In this article, the outcomes of the research are presented. In the following investigation, the outflow control coefficient and the gate control coefficient were determined. Sub-threshold swing reduces with the alteration in α_G but increases with the change in α_D when the diameter changes. Again, as the gate control coefficient (α_G) increases, the value of quantum capacitance decreases with a smaller diameter, but with a larger diameter, the quantum capacitance of the device does not vary significantly. About the drain control coefficient (α_D), the same phenomenon occurs as the diameter varies. The transconductance varies relative to the gate control coefficient (α_G) with the variation of diameter, which indicates that the conductance of the CNTFET increases with the variation of α_G. However, when the drain control coefficient (α_D) is increased alongside an alteration in diameter, the transconductance value stays almost unchanged.

Authors Contributions
All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

Availability of data and materials
Data presented in the manuscript are available via request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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