The Fundamental $1/f$ Noise and the Hooge Parameter in Semiconductor Quantum Wires

A. Balandin, *Member, IEEE*, K. L. Wang, *Fellow, IEEE*, Alexei Svizhenko, and S. Bandyopadhyay, *Senior Member, IEEE*

***Abstract*—We have calculated the Hooge parameter α_H characterizing fundamental $1/f$ noise in a free-standing intrinsic silicon quantum wire using microscopic noise theory. Our model takes into account quasi-one-dimensional confinement of both phonons and electrons. We find that at low temperatures, α_H can be reduced significantly by an external magnetic field which suppresses large-angle electron scattering. This allows one to quench $1/f$ noise. Futhermore, a magnetic field provides a convenient tool to probe the source of noise in quantum wires, and, to a certain degree, test the validity of the microscopic mobility-fluctuation quantum noise model itself.**

***Index Terms*—$1/f$ noise, magnetic field effects, phonons, quantum wires, silicon.**

I. Introduction

DESPITE the vast body of theoretical work on $1/f$ noise in bulk semiconductor structures [1]–[7], little attention has been paid to this ubiquitous phenomenon in low-dimensional systems such as quantum wires. This is somewhat surprising given that the strength of $1/f$ noise is generally found to increase in systems of small physical size [5]. Semiconductor quantum wires are small physical systems that provide a fertile ground for the study of fluctuations leading to $1/f$ noise. Such studies are important from the perspectives of both fundamental physics and device applications.

Unfortunately, the effects of low-dimensionality on $1/f$ noise are particularly difficult to investigate since there is no universally accepted $1/f$ noise theory even for bulk systems. No single model has been able to explain all the diverse results obtained under different experimental conditions and from different devices. At this time, there are two competing models that are invoked to explain noise data; the carrier density fluctuation model and the mobility fluctuation model. The former attributes noise to random trapping and de-trapping of free carriers by traps that have a particular distribution of time constants. McWhorter noted that such a distribution could arise naturally at a semiconductor-oxide interface from a spatially uniform distribution of tunneling depths to the trapping sites [8]. This model seems to work well for CMOS devices. We should point out that there is a body of work pertaining to random telegraph noise in mesocopic devices [9] caused by a single electron trap that supports the carrier density fluctuation model. On the other hand, the mobility fluctuation model attributes $1/f$ noise to spontaneous mobility fluctuation due to scattering of carriers. This model was successfully applied to a variety of material systems and structures ranging from long bulk resistors to short channel HEMT's. A related model attributes $1/f$ noise to random motion of impurities in a mesocopic device smaller than the phase-breaking length of electrons [10]. This model is purely quantum-mechanical and arises from quantum interference of electron waves scattered from a slowly moving impurity. It is relevant to cryogenic experiments where the phase-breaking length is large enough. Since we are concerned with room-temperature phenomena only, this model is not relevant.

We will adopt the generic mobility-fluctuation model and apply it to a free-standing intrinsic semiconductor quantum wire. The wire is assumed to be free of traps so that the carrier fluctuation model is summarily inapplicable at the outset. We further assume that the mobility fluctuates primarily because of lattice scattering. These simplifying assumptions allow us to investigate the fundmental noise limit in a low-dimensional structure and reveal the important role of spatial confinement of both carriers and phonons.

One of the frequently cited merits of a quantum wire is that elastic (e.g., impurity) scattering events are suppressed in such systems when only one transverse subband is occupied [11]. This feature is likely to reduce $1/f$ noise in very narrow wires at low temperatures when elastic scattering is predominant. An open question is what is the effect on $1/f$ noise when multiple subbands are occupied and inelastic (phonon) scattering dominates (e.g., at room temperature). One-dimensional (1-D) confinement of electrons constricts scattering phase space and tends to reduce scattering rate, but, at the same time, 1-D confinement of acoustic phonons increases the joint electron-phonon density of states and tends to increase the scattering rate at energies near the subband bottom [12]. Therefore, it is not clear apriori as to whether, on the average, $1/f$ noise actually increases or decreases as a result of electron and phonon confinement. In this paper, we seek an answer to this question and also examine the effects of a magnetic field on the fundamental $1/f$ noise.

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A. Balandin and K. L. Wang are with the Device Research Laboratory, Department of Electrical Engineering, University of California, Los Angeles, CA 90095 USA.

A. Svizhenko and S. Bandyopadhyay are with the Department of Electrical Engineering, University of Nebraska, Lincoln, NE 68588 USA.

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II. Theory

It is convenient to characterize the magnitude of $1/f$ noise in solids by the Hooge parameter. The spectral density of $1/f$ noise in a resistor obeys the empirical relation [2]–[4]

$$\frac{S_I(f)}{I^2} = \frac{\alpha_H}{fN} \tag{1}$$

where

$S_I(f)$ current spectral density;
f frequency;
N number of carriers in the sample;
α_H Hooge parameter.

The value of the Hooge parameter can be very different for different semiconductor structures and devices [1]–[7], ranging from 2×10^{-3} for long resistors or pn junction diodes to 1×10^{-5} for GaN HFET's [13] or 1×10^{-8} for short channel GaAs FET's and BJT's. One should note that (1) is the defining equation for the Hooge parameter itself and is model-independent [14].

In order to calculate α_H from the first principles, we use Handel's microscopic theory of $1/f$ noise. Quantum electro-dynamic theory defines the Hooge parameter via the fluctuation of the carrier cross sections during scattering. Our choice of Handel's theory over several other competing ones, including the most recent one [15], is justified by the fact that Handel's basic equation for α_H was confirmed in numerous experimental investigations, (e.g., [16] and [1]–[4]). Moreover, as it will be seen in the next section, a magnetic field can be used as a testing tool to assess the validity of the theory itself. Handel's theory is thus explicitly testable.

According to [7], (1) describes the so-called incoherent $1/f$ noise, which is dominant in very small devices or samples. The typical value of α_H in this case is on the order of 10^{-6}–10^{-9}. For large devices or "true" bulk samples, the concept of coherent state quantum noise was introduced [1], [7] which gives much larger values of the Hooge parameter $\alpha_H^{\rm coh} \sim 4.6\,10^{-3}$. One should note that a quantum wire with its extremely small cross section is always in the regime of "incoherent noise." Consequently, we should compare the Hooge parameter of a quantum wire with that of another small (but not quantum confined) "bulk" sample which is adequately described by the "incoherent formula" of (1).

Handel's microscopic theory of $1/f$ noise, associated with mobility fluctuation in a collision-dominated semiconductor structure, gives the following expression for the Hooge parameter [7]:

$$\alpha_H = \frac{4\alpha}{3\pi}\left[\frac{\langle(\Delta v)^2\rangle}{c^2}\right] \tag{2}$$

where α is the fine structure constant $(1/\alpha = 137)$, c is the speed of light, Δv is the change in velocity of an electron (or hole) due to a collision process, and the averaging denoted by $\langle\,\rangle$ is performed in k-space over all final scattering states weighted by the scattering rate, and then over all initial states weighted by the particle distribution function (which is the occupation probability of the initial state). This ensemble-averaging over the particle distribution function immediately shows that $1/f$ noise is not a single particle effect; rather, it is an ensmeble effect associated with all the carriers in a sample. Equation (2) has been widely used for noise characterization in MOSFET channels and two-dimensional (2-D) electron gas (2-DEG) of HEMT structures [1], so that it is reasonable to assume that the same formalism can be applied for quantum wires of finite lateral dimensions.

We will study a free-standing quantum wire of rectangular cross section subjected to an external transverse magnetic field. An electric field is applied along the wire axis to induce carrier transport (see the arrangement shown in the first inset in Fig. 1). The unusual approach of including a magnetic field in this study is intended to show later that such a field can suppress $1/f$ noise. To calculate $\langle(\Delta v)^2\rangle$ in such a system, we first average over all final scattering states, as shown in (3) at the bottom of the page, where k and k' are the initial and final wave vectors of the electron along the wire axis, (m,n) and (m',n') are the initial and final transverse subband indices along the width and thickness of the wire, $v_{m,n} = (1/\hbar)(\partial E_{m,n}/\partial k_{m,n})$ is the electron velocity in a particular subband (m,n), B is the flux density associated with the externally applied magnetic field, $S(k_{m,n}, k'_{m',n'}, \pm\gamma, B)$ is the scattering rate associated with transition from an energy state $E(k_{m,n}, B)$ in the confined magneto-electric subband (m,n) to an energy state $E'(k'_{m',n'}, B)$ in another confined magneto-electric subband (m',n') by absorbing or emitting a phonon with the longitudinal wave vector γ and energy $\hbar\omega_\gamma$. Once $(\Delta v)^2(k)$ is found, the quantity $\langle(\Delta v)^2\rangle$ is evaluated by ensemble averaging over the initial states. We assume that the initial states are occupied according to a displaced Maxwellian distribution function $f(k_{m,n}) = \exp[-m^*(v_{m,n} - v_d)^2/(2kT)]$ where T is the lattice temperature and v_d is the drift velocity. A more appropriate distribution function can be found from Monte Carlo simulation and this is reserved for future work. The ensemble averaged value is finally given as

$$\langle(\Delta v)^2\rangle = \frac{\sum_{m,n}\int_0^\infty (\Delta v)^2(k_{m,n}) f(k_{m,n})\,dk_{m,n}}{\sum_{m,n}\int_0^\infty f(k_{m,n})\,dk_{m,n}}. \tag{4}$$

Calculation of the scattering rate S in (3) has been described by us in a number of previous publications [17]–[20]. Briefly speaking, we first find the electron wave functions and density of states in each magnetoelectric subband by solving the Schrödinger equation numerically [21]. The phonon modes and their dispersion relations are found by solving the elasticity equation [20], [22]. The scattering rates are then found from Fermi's Golden Rule [22].

$$(\Delta v)^2(k_{m,n}) = \frac{\sum_{m',n'}\int_0^\infty\int_0^{\gamma_{\max}} (v(k_{m,n}) - v'(k'_{m',n'}))^2 S(k_{m,n}, k'_{m',n'}, \pm\gamma, B)\,dk'_{m',n'}\,d\gamma}{\sum_{m',n'}\int_0^\infty\int_0^{\gamma_{\max}} S(k_{m,n}, k'_{m',n'}, \pm\gamma, B)\,dk'_{m',n'}\,d\gamma} \tag{3}$$

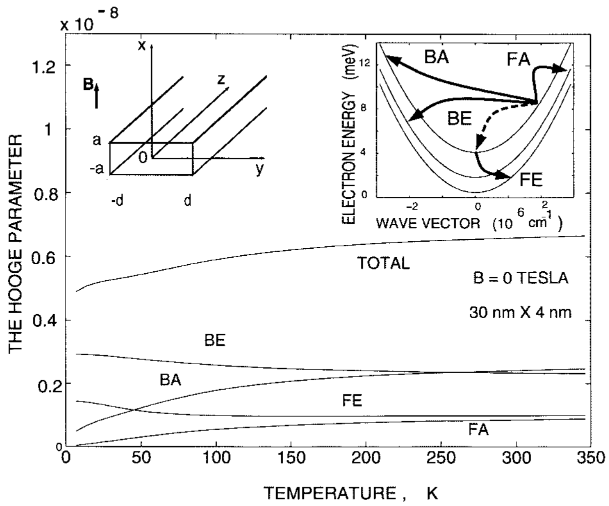

Fig. 1. Hooge parameter versus temperature. No magnetic fieldis present. The first insert on the left shows the geometry of the quantum wire and the orientation of the magnetic field. The second inset shows four different scattering processes: 1) backward emission (BE), 2) backward absorption (BA), 3) forward emission (FE), and 4) forward absorption (FA).

Lattice scattering has been identified as the major source of $1/f$ noise in a number of materials and devices including 3-D and 2-D systems [2], [23]. In [23], the authors found that polar optical phonon scattering is particularly responsible for $1/f$ noise in GaAs HEMT's. In intrinsic silicon wires, the most important lattice scattering mechanism is acoustic phonon scattering. Thus, we will calculate $\langle(\Delta v)^2\rangle$ considering only electron-acoustic phonon scattering. Calculation of scattering rates for this mechanism has been described in [20].

III. Results and Discussion

In Fig. 1, we plot the Hooge parameter versus temperature for a silicon quantum wire of width 30 nm and thickness 4 nm. We make no distinction between electron and lattice temperature since we assume that the electrons are not heated. Only one transverse subband along the thickness is occupied even at the highest temperature, but 34 transverse subbands along the width are considered. In the plot, we show explicitly the contributions from four different processes: backward emission (BE), forward absorption (FA), backward absorption (BA) and forward emission (FE). Forward processes are those in which an electron gains momentum from the phonon by being scattered in the forward direction. Backward scattering causes momentum loss. Emission (absorption) processes involve the emission (absorption) of a phonon. These four types of transitions in a subband are schematically depicted in the second insert of Fig. 1. Material parameters used in the calculation of α_H are the following: electron effective mass $m^* = 0.19m_0$, longitudinal acoustic velocity $s_l = 9.04 \times 10^5$ cm/s and electron drift velocity $v_d = 1 \times 10^7$ cm/s.

Obviously, the change Δv associated with both forward absorption (FA) and forward emission (FE) is small (see the second insert of Fig. 1) and therefore these processes do not contribute significantly to the Hooge parameter. Backward scattering involves a much larger Δv since it typically turns an electron around. Therefore, its contribution to the Hooge parameter is much larger. In the case of backward absorption (BA), this contribution increases with temperature since the phonon occupation probability (and hence the scattering probability) increases with temperature. At low temperatures, the phonon occupation probability (which we assume is the Bose–Einstein factor) increases exponentially with temperature $(\sim\exp\{-\hbar\omega/kT\})$, whereas at high temperatures, it increases linearly $(\sim kT/\hbar\omega)$. This feature is reflected in the temperature dependence of the Hooge parameter.

Unlike absorption, emission of phonons has two components: spontaneous and stimulated. The former is relatively temperature-independent since it does not depend on the phonon occupation probability. The latter is proportional to this probability and hence depends on temperature. The contribution of backward emission (BE) decreases with increasing temperature. This happens because at higher temperatures, higher energy phonons are available which permit the inelastic process shown by the broken line in the insert of Fig. 1. Note that this process results in significant energy relaxation, but relatively small Δv and hence a relatively small contribution to the Hooge parameter. In contrast, the quasi-elastic backward emission process, shown by the solid line, results in insignificant energy relaxation, but a much larger Δv. At low temperatures, only the quasi-elastic process is allowed since the inelastic process (broken line) is blocked by energy conservation. The latter requires high energy phonons which are scarce at low temperatures. Therefore, the quasi-elastic process dominates and the contribution to the Hooge parameter is large. At higher temperatures, both processes are allowed, but the inelastic process (broken line) is preferred since the scattering rate is proportional to the electron-phonon joint density of final states and the electron density of states is very large at a subband bottom (in fact, the density of states has a Van Hove singularity at the subband bottom). Thus, the dominant scattering process at higher temperatures does not contribute much to the Hooge parameter and, as a result, the latter drops. This explains the decreasing temperature dependence of the contribution of emission processes to the Hooge parameter.

Examining the magnitude of α_H in Fig. 1, we find that it is less than or comparable to that found in mesoscopic three-dimensional samples. Therefore, 1-D confinement can reduce $1/f$ noise. However, it is not necessarily universal and may depend on the dimensions of the wire and the material parameters.

In Fig. 2, we show the temperature dependence of the Hooge parameter when an external magnetic flux density of 10 T is applied. The magnetic field strongly decreases the Hooge parameter at low temperatures for two reasons. First, at low temperatures, the dominant scattering process is elastic or quasi-elastic backscattering that turns an electron around through a 180° deflection. This particular process is strongly suppressed by a magnetic field. The cause of this suppression has been elucidated in previous publications [17], [20]. As a result of this suppression, the dominant contribution to the Hooge parameter virtually disappears at low temperatures. At higher temperatures, other inelastic scattering mechanisms are more important and these are not suppressed as much by a magnetic field. Consequently, the Hooge parameter is not quenched at higher temperatures. A second reason for the low-

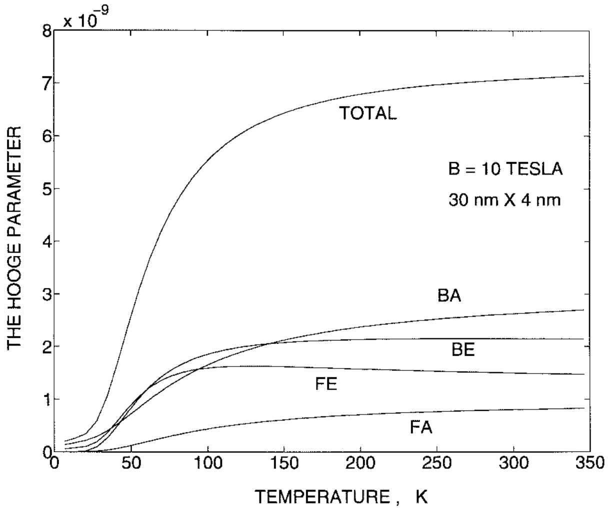

Fig. 2. Hooge parameter versus temperature when a magnetic flux density of 10 T is applied.

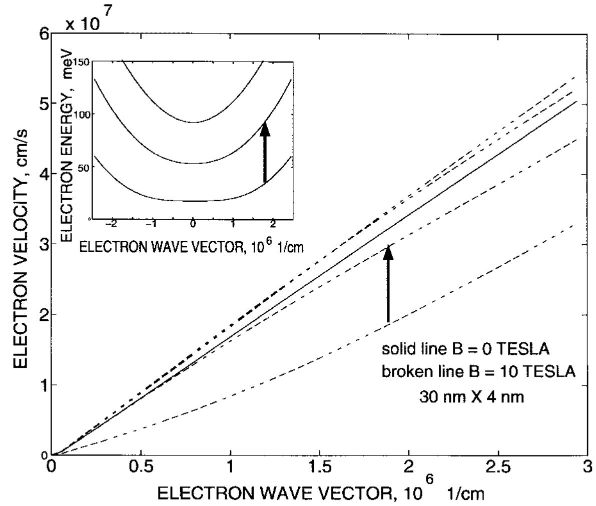

Fig. 3. Velocity versus wavevector relation for the quantum wire at 0 and 10 T. The width of the wire is 30 nm and the thickness is 4 nm. In the absence of a magnetic field, velocity is uniquely related to wavevector and the relation is linear (the conductionband is assumed to be parabolic). In a magnetic field, the relationshipis nonlinear and different in different subbands. A transitionis shown to indicate that the velocity can change in an inelastic inter-subband scattering process without changing momentum. The insert shows energy-wavevector relations for magnetoelectricsubbands in a quantum wire at a magnetic flux density of 10 T. The same transition is shown here as well.

temperature suppression of α_H is that a magnetic field is much more effective in suppressing quasi-elastic backscattering of high velocity electrons than low velocity electrons [17]–[20]. At low temperatures, the displaced Maxwellian distribution, $f(k_{m,n}) \propto \exp\{-m^*(v_{m,n} - v_d)^2/2kT\}$, has a sharp peak around the drift velocity v_d so that most electrons have a reasonably high velocity (provided of course the driving electric field is reasonably high) and the suppression of the Hooge parameter is very pronounced. At higher temperatures, the distribution is smeared out owing to thermal fluctuations. As a result, backscattering is not significantly suppressed for electrons in the low velocity tail of the distribution. Consequently, we can see a significant quenching of the Hooge parameter only at low temperatures.

At very high temperatures, the Hooge parameter actually increases in a magnetic field. At these temperatures, many magneto-electric subbands are occupied and an electron can scatter inelastically between two such subbands *without* changing momentum $\hbar k$, but still changing velocity. Fig. 3 shows such a process. (The reverse process involving a momentum change but no velocity change is also possible but not of interest here). These unusual processes are possible since momentum is not proportional to velocity in a magnetic field even if the conduction band is parabolic. Such transitions are frequent scattering events since they require phonons with zero wavevector which are abundant. Note that they also require phonons which have a nonzero energy. Thus, this class of scattering processes require three ingredients:

1) acoustic phonon *confinement* since only confined acoustic phonons can have zero wavevector and yet finite energy;
2) a magnetic field;
3) relatively high temperatures since high-energy phonons are required to affect the transitions.

It is the introduction of this new class of scattering processes (and their strong contribution to the Hooge parameter) at high temperatures that causes the latter to increase in a magnetic field at elevated temperatures.

Our calculated temperature dependence of the Hooge parameter is consistent with the experimental and theoretical results reported by Tacano [16] for a mesoscopic n-GaAs filament. For analysis of his experimental data, Tacano used Handel's microscopic theory and found excellent agreement. The absolute value of α_H at $T = 20$ K in our case is about 5×10^{-7} which is comparable with the experimental values of 10^{-8}–10^{-7} presented in Fig. 4 of [16]. Our model is significantly different from the one used by Tacano due to the fact that we include spatial confinement of carriers and phonons in a quantum wire.

The predicted effect of a magnetic field on the Hooge parameter can be used to distill out the contribution of $1/f$ noise from the background of Johnson and other types of noise and to test the validity of various noise models, particularly the one due to Handel. Experimental data reported in [24] suggest that $1/f$ noise in n-InSb is very sensitive to an external magnetic field applied perpendicular to current flow. Further magnetotransport measurements, particularly at low temperatures, are needed in order to clarify the effects of a magnetic field on $1/f$ noise and to separately identify various noise sources.

IV. Conclusion

We have calculated the Hooge parameter characterizing fundamental $1/f$ noise in a quantum wire. Our model rigorously takes into account spatial confinements of acoustic phonons and electrons in a quantum wire. It was also shown that the Hooge parameter can be suppressed significantly by an external magnetic field at low temperatures. Thus, we may be able to use a tunable magnetic field to distinguish $1/f$ noise from other sources of noise (such as interface charge fluctuation and noise associated with carrier density fluctuations) in an experimental situation. The calculated magnetic field dependence of the Hooge parameter may also be used to test the microscopic $1/f$ noise theory itself.

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A. Balandin (M'96) was born in Nizhny Novgorod, Russia, on April 30, 1968. He received the M.S degree (cum laude) in applied physics and mathematics from the Moscow Institute of Physics and Technology - Dolgoprudny, Russia, in 1991, and the M.S.E.E. and Ph.D. degrees in electrical engineering from the University of Notre Dame, Notre Dame, IN, in 1995 and 1996, respectively.

From 1996 to 1997, he was a Research Associate in the Quantum Device Laboratory, University of Nebraska, Lincoln. In 1997, he joined the Device Research Laboratory, Department of Electrical Engineering, University of California, Los Angeles, as a Research Engineer. His research interests are in electronic materials and devices, low-dimensional phenomena, nonlinear optics, noise theory and measurements, thermoelectrics, quantum and nanoelectronic computer architectures.

Dr. Balandin is a member of Eta Kappa Nu.

K. L. Wang (S'68–M'70–SM'78–F'92) received the M.S. and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1966 and 1970, respectively.

From 1970 to 1972, he was an Assistant Professor at MIT. He joined General Electric Corporate Research and Development Center as a Physicist/Electrical Engineer from 1972 to 1979. Meanwhile, he also served as an Adjunct Professor in the Department of Physics at State University of New York, Albany. Since 1982, he has been a Professor of Electrical Engineering at the University of California, Los Angeles, where he was also Chairman of the Department from 1993 to 1996. He has published over 200 papers in various areas of semiconductor material and devices including those relating to surfaces and interfaces, MBE growth, nanostructures, and devices, as well as processing technology.

Dr. Wang is a Guggenheim Fellow and received the J. H. Ahler Achievement Award (1991), SRC Invention Awards (1989–1996), and SRC Technical Excellence Award (1996).

Alexei Svizhenko was born in Kyiv, Ukraine, on January 10, 1973. He received the B.S. and M.S. degrees in solid state and semiconductor physics from Moscow Institute of Physics and Technology, Russia, in 1993 and 1995, respectively, and the Ph.D. degree in electrical engineering from the University of Nebraska, Lincoln, in 1999. He is currently a Postdoctoral Fellow at the University of Nebraska working on a joint project with NASA-Ames, Moffett Field, CA. His research interests include theoretical simulation of transport and noise in quantum structures and devices.

S. Bandyopadhyay (S'81–M'82–SM'89) received the B.Tech degree in electronics and electrical communications engineering from the Indian Institute of Technology, Kharagpur, in 1980, the M.S. degree in electrical engineering from Southern Illinois University, Carbondale, in 1982, and the Ph.D. degree in electrical engineering from Purdue University, West Lafayette, in 1985.

Currently, he is a Professor in the Department of Electrical Engineering, University of Nebraska, Lincoln, and directs the Quantum Device Laboratory at the same university. His research interests are in nanostructured systems. He has authored and coauthored more than 200 technical articles in this general field, co-edited six volumes, co-organized eleven international conferences, and has served as Guest Editor of special issues of journals dedicated to this field.

Dr. Bandyopadhyay is a member of Tau Beta Pi, Eta Kappa Nu, Sigma Pi Sigma, the American Physical Society, and the Electrochemical Society.