

An Analytical Theory of Avalanche Breakdown in p-n Junctions Derived From Semiconductor Band Structure

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Abstract—This article presents a comprehensive analytical theory for the avalanche breakdown process in p-n junction diodes to address the critical reliance on empirical models in the design of avalanche photodiodes (APDs) and single-photon avalanche diodes (SPADs). The proposed model is derived from fundamental carrier continuity equations and impact excitation probability. Eventually, it yields closed-form expressions for the avalanche current density and the breakdown voltage. It demonstrates excellent agreement with experimental current–voltage characteristics across various semiconductors (Si, GaN, 4H-SiC, and InP) and a wide temperature range. TCAD simulations are also adopted to validate this model. The theory establishes a unified, physics-based criterion for defining the avalanche breakdown voltage, revealing its functional dependence on material parameters (bandgap, dielectric constant, and mean-free path) and doping concentrations. Significantly, it explicitly predicts the theoretical minimum and maximum limits for the breakdown voltage in a given material, which were well known but only implicitly reflected in previous empirical models. This work provides a rigorous theoretical framework for the steady-state dark avalanche current for the targeted design of diverse avalanche-based devices, ranging from low-breakdown-voltage SPADs for integrated quantum photonics to high-breakdown-voltage power devices, moving beyond trial-and-error approaches.

Index Terms—Analytical theory, avalanche breakdown voltage, avalanche current, avalanche effect, impact excitation.

I. INTRODUCTION

PHOTONICS-BASED quantum computing has emerged as a prominent architecture due to its inherent advantages in high-speed information processing and enhanced security for quantum communications [1], [2]. Among its various implementations, Si-based photonic quantum computing stands out

for its exceptional compatibility with mature complementary metal-oxide-semiconductor (CMOS) fabrication processes [2], [3]. This compatibility offers a compelling path toward scalable, cost-effective, and highly integrated quantum systems. The performance of such systems critically depends on the efficiency and integration capability of single-photon detectors (SPDs), which convert quantum optical signals into measurable electrical currents [4], [5]. Single-photon avalanche diodes (SPADs) fabricated from silicon-germanium (SiGe) alloys present a highly promising solution [5]. Leveraging standard silicon foundry processes, SiGe SPADs offer a natural pathway for on-chip integration with silicon photonic components such as waveguides and modulators, making them a key enabler for fully integrated photonic quantum processors. Despite their integration advantages, the design and optimization of avalanche photodiodes (APDs) and SPADs have largely relied on empirical models and experimental iterations. A theoretical framework, rigorously derived from fundamental semiconductor physics, is notably absent. This gap hinders the design and performance exploration of APDs, making it difficult to systematically elucidate the relationship between material parameters and avalanche breakdown characteristics. Consequently, the development of low-voltage SPADs for sensitive detection remains constrained.

The widely accepted avalanche current expression proposed by Sze and Gibbons [6], [7] is as follows:

$$J(W) = \frac{1}{1 - \int_0^W \beta dx} J(0) \quad (1a)$$

where $M = 1 / (1 - \int_0^W \beta dx)$ is defined as the multiplication factor, W is the depletion region width, $\beta = c_1 \exp[-(c_2/\mathcal{E}(x))^m]$ is the field-dependent ionization rate, $\mathcal{E}(x)$ is the electric field within the depletion region, c_1 , c_2 , and m are the just empirical parameters, $J(0)$ is the initial current density at the depletion region edge. The corresponding breakdown voltage V_B proposed by Sze and Gibbons [6], [7] is expressed as

$$V_B = \frac{\epsilon_s \mathcal{E}_c^2}{2qN} \quad (1b)$$

where $\mathcal{E}_c$ is the critical electric field of the avalanche process, ϵ_s is the dielectric constant of the semiconductor, and N is the doping concentration of the lightly doped side. With this framework, numerous models have been developed to describe avalanche processes, including the Chynoweth model [8], Selberherr model [9], Okuto–Crowell model [10], Crowell–Sze

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model [11], etc. Despite differences in their mathematical forms, these models share a common physical foundation, i.e., the use of a field-dependent impact ionization rate to describe carrier multiplication. However, a key limitation of these approaches is that the ionization rate is generally approximated empirically or semiempirically, often involving complex mathematical forms. These models, therefore, are mostly used in TCAD software because they require significant computing capacity to numerically calculate avalanche current. This limitation hinders both physical interpretation and efficient device design. Accurate analytical modeling or prediction of avalanche behavior remains challenging in the absence of closed-form expressions. Such mathematical modeling of device characteristics forms the basis of SPICE models required for circuit-level design and simulation. The fundamental difficulty arises from the long-standing lack of an analytical expression for the carrier ionization rate, which forces avalanche processes to be described using empirical or semiempirical equations. Moreover, in the avalanche breakdown voltage (1b), the empirical parameter critical electric field $\mathcal{E}_c$ is typically affected by factors such as temperature and material properties. The mathematical relationships among these variables have not yet been established. These limitations highlight the need for a theoretical framework with a rigorous description of physical progress that yields an explicit analytical expression for the avalanche process.

To address these fundamental challenges, in the present work we have established an analytical theory for the avalanche multiplication process based on semiconductor band theory. While our work shares the same fundamental physical picture of energy-based impact ionization, it differs in its methodological approach. Instead of following the same previous path of empirically modeling the field-dependent ionization rate, we manage to derive the analytical expression of the impact ionization rate. By combining it with the fundamental carrier continuity equation, we eventually obtain closed-form analytical expressions for the avalanche current and avalanche breakdown voltage. The proposed model demonstrates excellent agreement with experimental data reported in the literature and TCAD simulation results. This model breaks through the limitations of traditional empirical models and links the avalanche current with material properties and device structural parameters, such as bandgap, carrier drift velocity, mean-free path, doping concentration, etc. Furthermore, the key physical parameters extracted from our theory are consistent with established theoretical and experimental values, thereby validating the correctness of the avalanche theory. This theory enables the systematic prediction of the avalanche breakdown voltages for various semiconductor materials, identifying their theoretical minima and maxima. It thus provides a rigorous theoretical foundation for the targeted design of both low-breakdown-voltage SPADs for quantum photonic applications and high-breakdown-voltage power devices.

II. RESULTS AND DISCUSSION

For most widely used semiconductors, electrons have a larger mobility than holes. As a result, the impact ionization occurs at a lower electric-field intensity for electrons. For this reason, in this article, we only investigate the electron impact ionization for the avalanche process. Nevertheless, the

theory developed below is also applicable to hole impact ionization. The electron impact ionization process is shown in Fig. 1. Suppose electrons at Location ① are in thermal equilibrium state, meaning that the electrons in the conduction band follow the Boltzmann distribution $f(\xi)$ (see the electron distribution in the upper part of Fig. 1). In the next mean-free path, electrons will be accelerated by the electric field $\mathcal{E}$, becoming hot electrons by gaining a kinetic energy of $q\mathcal{E}\ell$ with q being the unit of charge and ℓ the mean-free path. At Location ②, hot electrons lose their kinetic energy during inelastic collisions with the semiconductor, reaching thermal equilibrium at Location ③. The lost kinetic energy, if larger than the bandgap of the underlying semiconductor, i.e., $q\mathcal{E}\ell \geq E_g$, has a probability to excite electrons from the valence band into the conduction band, corresponding to the energy transfer process, as shown in Fig. 1. This process can be described by (2a) in which W_i is the electron impact ionization rate and W_0 is the impact ionization coefficient [12], [13]

$$W_i = W_0 \int_0^\infty g(\xi) f(\xi) g(\xi') \text{step}(\xi - E_g - \xi') d\xi d\xi' \quad (2a)$$

where $g(\xi) = g_0(\xi)^{1/2}$ is the density of states of an electron with $g_0 = m_c^{3/2}/(2\pi^2\hbar^3)$, the Boltzmann distribution of charge carriers $f(\xi) = f_0 \exp(-\xi/k_B T)$, the carrier effective mass m_c and the reduced Planck constant $\hbar$. ξ and ξ' stand for the energy level at the ground state and the energy level of hot electrons after gaining kinetic energy of $q\mathcal{E}\ell$. E_g is the energy band gap of the underlying semiconductor. After plugging these parameters, (2a) can be solved to yield (2b)

$$W_i \approx \gamma n (q\mathcal{E}\ell \geq -E_g)^{\frac{3}{2}} \quad (2b)$$

where $\gamma = 2aW_0g_0/(3(\pi)^{1/2}(k_B T)^{3/2})$, $a \approx 0.00357$ is a numerical constant generated during numerical simplification and n is the carrier concentration. The detailed simplification steps are presented in Section I of Supplementary Information (SI). Similarly, when free carrier energy is lower than bandgap energy, i.e., $q\mathcal{E}\ell \leq E_g$, the corresponding impact excitation probability is provided in Section I of SI. The dependence of impact excitation probability on carrier energy, ranging from 0 to 5 eV, is also plotted therein. The results demonstrate that W_i decays exponentially by several orders of magnitude once the carrier energy falls below the bandgap energy. It gradually approaches saturation after carrier energy exceeds the bandgap energy. Therefore, the bandgap energy is chosen as the threshold energy in this work, consistent with previous studies based on first-principles calculations [14], [15].

Equation (2b) is the electron impact ionization rate in each mean-free path. The avalanche process is caused by a series of these impact ionization incidents, which is governed by the steady-state continuity as shown in (3a)

$$D_n \frac{d^2 n}{dx^2} - \frac{d(nv_{drift})}{dx} + G_n - R_n = 0. \quad (3a)$$

For the avalanche process that occurs at high electric-field intensity, the terms associated with diffusion current and recombination rate in the depletion region are negligible in comparison with the one associated with drift current. In particular, the impact generation rate is always 3–4 orders of magnitude higher than the recombination rate according to our TCAD simulation results in Section II of SI. Similarly, the diffusion current is approximately on the order of

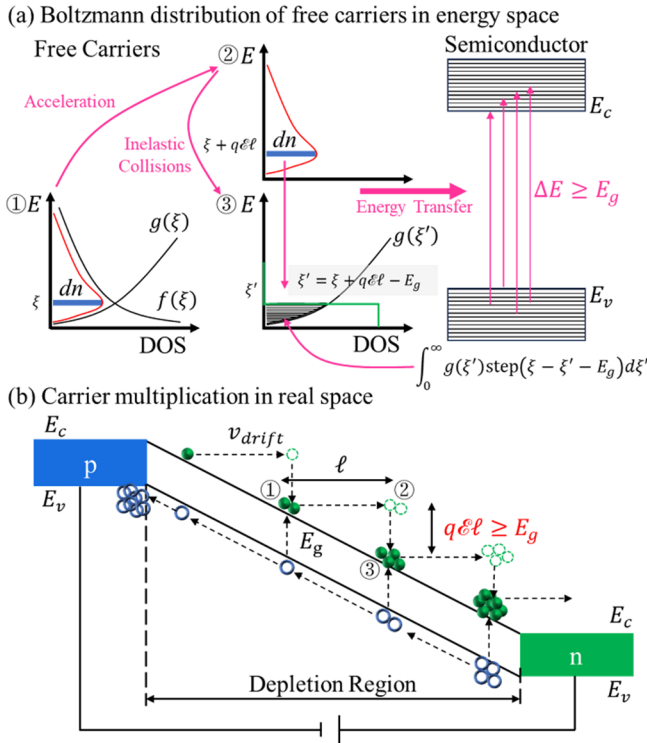


Fig. 1. Schematic of avalanche processes based on electron impact ionization. (a) Carrier density of states in energy space described by Boltzmann statistics and the energy exchange processes of hot carriers. (b) Schematic of the carrier avalanche effect in real space. First, electrons at position ① drift toward position ② in the depletion region, gaining an average energy of $q\epsilon\ell$, where ϵ is the electric field and ℓ is the electron mean-free path. Second, these hot electrons undergo inelastic scattering processes. When their energy exceeds a threshold, part of their energy can be transferred to the system to generate additional electron-hole pairs via impact ionization. After scattering, electrons relax toward lower energy states ③. The generated carriers, together with the original carriers, are subsequently accelerated again by the electric field. Through repeated stochastic cycles of acceleration and scattering, a chain multiplication process is established, leading to the carrier avalanche effect. The labels ①–③ in (a) correspond to the density of states of free carriers at the spatial positions indicated in (b).

1 mA/cm² near the breakdown voltage, whereas the avalanche current reaches 100 mA/cm². The contribution of the diffusion component will be further reduced as the reverse voltage increases. However, it is noteworthy that in the vicinity of the breakdown voltage, the impact generation rate does not significantly exceed the recombination and diffusion. In this transitional regime, the present model is not expected to fully capture the gradual onset of avalanche multiplication near the breakdown voltage. For the carrier drift velocity, it is strongly field-dependent. For example, the drift velocity of silicon increases from 5.7×10^5 cm/s at an electric field of 4×10^2 V/cm to 2.5×10^7 cm/s at 4×10^5 V/cm. Such strong field dependence is important when analyzing the reverse current over the entire reverse voltage range. Luckily, our proposed model focuses exclusively on the avalanche breakdown regime of a p-n junction. In practice, the device is usually operated within a relatively narrow voltage range, typically only a few volts beyond the breakdown voltage. Within this narrow voltage window, the electric field does not change significantly with increasing voltage according to the TCAD simulation results in Section II of SI. Therefore,

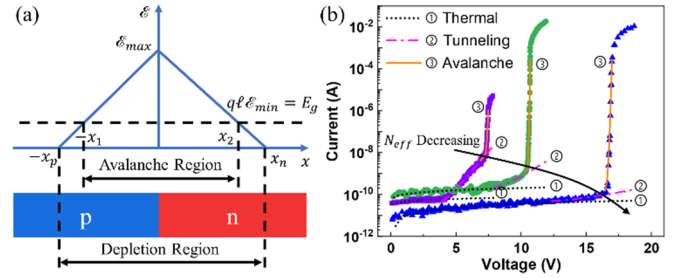


Fig. 2. (a) Schematic of an avalanche diode based on a p-n junction. (b) Reverse current of a silicon p-n junction from [18], [19], and [20], which include thermal generation, tunneling effect, and avalanche effect.

free carriers rapidly reach their saturation velocity, and further increases in reverse voltage lead to negligible change in drift velocity. From a spatial perspective, taking a representative doping concentration of 10^{17} cm⁻³ on both sides, for example, the maximum electric field is 4.0×10^5 V/cm. The minimum electric field for the onset of impact generation is $\sim 1.5 \times 10^5$ V/cm. Correspondingly, the drift velocity of silicon rises from 1.024×10^7 to 1.045×10^7 cm/s [16]. Therefore, in the avalanche regime, it is reasonable to assume a constant saturated drift velocity, i.e., $v_{drift} = v_s$. For other materials like Ga₂O₃, when the electric field increases from 1.5×10^5 V/cm to 4.0×10^5 V/cm, the drift velocity increases from 1.6×10^7 to 2.6×10^7 cm/s [17]. This difference is indeed larger than that of Si but still remains within an acceptable range to neglect the spatial difference in drift velocity.

The generation rate G_n without light illumination is the impact ionization rate $G_n = W_i = \gamma n(q\epsilon\ell - E_g)^{3/2}$. In the end, the continuity (3a) can be simplified into (3b). Note that with light illumination, an additional constant generation rate should be added to the right side of (3b), making it nonintegrable. In addition, this optical generation rate may not be uniform within the depletion region, which makes the carrier continuity equation more complicated

$$v_s \frac{dn}{dx} = \gamma n (q\epsilon\ell - E_g)^{3/2}. \quad (3b)$$

For a regular p-n junction with a wide p-type and n-type region as shown in Fig. 2(a), the border of the depletion region is labeled as $-x_p$ and x_n where the electric-field intensity is zero. When an avalanche process occurs, the electric-field intensity must meet the impact ionization condition $q\epsilon\ell \geq E_g$. The border of this region is labeled as $-x_1$ and x_2 as shown in Fig. 2(a). Given this boundary condition, the electron avalanche current density $J_n = qnv_s$ is derived as (4a). The detailed derivation steps are given in Section III of the SI

$$J_n = J_0 e^{\alpha[q\ell\epsilon_{max} - E_g]^{5/2}} \quad (4a)$$

where the current density prefactor $J_0 = qv_s n(-x_1)$ with $n(-x_1)$ being the electron concentration at $x = -x_1$. The prefactor α is defined as $\alpha = (2\gamma\epsilon_s)/(5qv_s\ell N_{eff})$ with the effective doping concentration $N_{eff} = (N_A N_D)/(N_A + N_D)$ and the dielectric constant ϵ_s of the semiconductor. The maximum electric field is $\epsilon_{max} = (2q(V_{bi} + V_R)N_{eff})^{1/2}/\epsilon_s$ with V_R and V_{bi} being the applied reverse bias and the built-in potential of the p-n junction, respectively. When (4a) is applied to fit experimental data, three parameters J_0 , α , and ℓ will be extracted (the bandgap E_g is fixed at a given value). From

these extracted parameters, the impact excitation probability coefficient γ and the initial carrier concentration $n(-x_1)$ can be further calculated, as the effective doping concentration N_{eff} , dielectric constant ϵ_s , built-in potential V_{bi} , and carrier saturation velocity v_s are given.

It can be seen from Fig. 2(a) and (4a) that the avalanche process will become dominant under the condition of $q\ell\mathcal{E}_{max} \geq E_g$. Clearly, the avalanche breakdown voltage V_B , which is the minimum reverse bias V_R to maintain the above inequality, is given in the following equation:

$$V_B = \frac{\epsilon_s E_g^2}{2q^3 \ell^2 N_{eff}} - V_{bi}. \quad (4b)$$

In some cases, photodiodes are often made in the form of a PIN structure to widen the depletion region for full absorption of photons. The avalanche current and the breakdown voltage can be further simplified as shown in Section IV of SI. In particular, the avalanche current with light illumination can be analytically derived, which also fits the experimental data well. The parameters extracted from the fittings are coherent and consistent with previous reports. See detailed discussions in Section IV of SI.

Interestingly, under appropriate simplified conditions, (4b) naturally reduces to the classical avalanche breakdown voltage expression (1b) proposed by Sze and Gibbons [6], [7]. First, in typical device configurations, the first term on the right-hand side of (4b) is generally much larger than the built-in potential V_{bi} . Therefore, it is reasonable to neglect V_{bi} . Second, for an asymmetrically doped p-n junction, the effective doping concentration N_{eff} can be reduced to $N_{eff} \approx N_D = N$ in the case of $N_A \gg N_D$. Furthermore, by taking the maximum electric field near avalanche breakdown as the critical electric field, i.e., $\mathcal{E}_{max} = \mathcal{E}_c$ and substituting the impact ionization condition $q\ell\mathcal{E}_{max} \geq E_g$ into (4b), the breakdown voltage can be simplified to $V_B = (\epsilon_s \mathcal{E}_c^2)/(2qN)$, which is exactly (1b) proposed by Sze and Gibbons [6], [7]. This result demonstrates that the avalanche breakdown voltage derived in this work converges to the classical semiempirical expression under appropriate simplifications, thereby confirming the consistency and validity of the present theoretical framework. More importantly, unlike conventional approaches based on empirical or semiempirical formulas, our model provides an analytical expression for the avalanche breakdown voltage with clear physical meanings. The derived equation explicitly links the breakdown behavior to intrinsic material parameters and device doping concentrations that can be of great help to the device design.

For an avalanche p-n junction diode, the leakage current originates from three sources [6]: thermal generation, tunneling, and avalanche effect, which are labeled as ①, ②, and ③ in Fig. 2(b), respectively. The thermal generation current is linearly proportional to $(V_R)^{1/2}$, while the tunneling current increases exponentially with the reverse bias V_R . At small voltages, the thermally generated electrons drift through the depletion region under an electric field. In this case, according to traditional semiconductor device theory, the reverse current is proportional to the depletion region width. These carriers that physically move inside the depletion region therefore have the potential to gain sufficient energy from the electric field once the reverse voltage is further increased. On the contrary, the tunneling current arises predominantly from field-assisted

band-to-band tunneling or trap-assisted tunneling processes in localized high-electric-field regions [21]. In this case, the free carriers directly tunnel through the potential barrier. This mechanism dominates the reverse-bias current within the moderate voltage range. Beyond the avalanche breakdown voltage, the carriers in the depletion region start to gain sufficient energy to excite more free carriers. Avalanche current also begins to dominate the reverse-bias current of the device. In most cases, tunneling current is undesirable in avalanche devices, because it can substantially increase the dark current and consequently degrade the performance of photodetectors. The tunneling current can be suppressed simply by increasing the depletion region width. As shown in Fig. 2(b), as the effective doping concentration N_{eff} decreases, the depletion region becomes wider, leading to a significant suppression of the tunneling current. Meanwhile, the avalanche breakdown voltage gradually decreases. The underlying physical mechanism of this phenomenon can be well explained by our model and will be discussed in detail later.

The avalanche current follows a superexponential dependence on V_R given in (4a), which provides excellent agreement with the experimental data as shown in Fig. 2(b). Taking the purple data in Fig. 2(b) for example, it yields an initial carrier concentration $n(0)$ of $3.64 \pm 0.27 \times 10^3 \text{ cm}^{-3}$, a mean-free path ℓ of $8.43 \pm 0.07 \text{ nm}$ and impact excitation probability coefficient γ of $3.06 \pm 0.01 \times 10^{17} \text{ eV}^{-3/2} \text{ s}^{-1}$. Regarding the mean-free path, we will conduct a more detailed discussion based on the temperature-dependent results later. Here, we would like to discuss the impact excitation probability γ first. According to the definition of γ , it is related to temperature, inherent properties of the semiconductor lattice, and the wave function of electrons. Different materials, devices, and external conditions such as temperature may lead to different γ values. The larger the γ value, the greater the impact of excitation probability between electrons and semiconductors. Currently, no closed-form analytical expression is available for this coefficient. To further evaluate its magnitude and consistency, we performed TCAD simulations on 28 Si-based avalanche diodes with different doping concentrations ranging from 10^{14} cm^{-3} to $4 \times 10^{18} \text{ cm}^{-3}$, as presented in Section V of SI. These simulations provide a controlled framework that minimizes the influence of external factors present in experimental measurements, such as temperature fluctuations and measurement-related uncertainties. The proposed model shows excellent agreement with all simulated I-V characteristics across this wide doping range. The corresponding extracted parameters are also provided therein. We find that most of the impact excitation coefficients are on the order of $10^{16} \text{ eV}^{-3/2} \text{ s}^{-1}$, which is close to the values extracted from experimental studies. These results further support the physical reliability and robustness of the proposed model.

To further validate the theoretical model presented above, we analyze the I-V curves of a silicon avalanche diode at different temperatures by fitting with (4a), shown in Fig. 3(a) [22]. It is worth noting that temperature-dependent effects play a critical and complex role in avalanche processes. A fully rigorous description would require explicit treatment of nonequilibrium carrier dynamics, which is beyond the scope of the present analytical framework. Therefore, these effects are incorporated through effective parameters, including bandgap energy, mean-free path, and carrier velocity in Sections VI

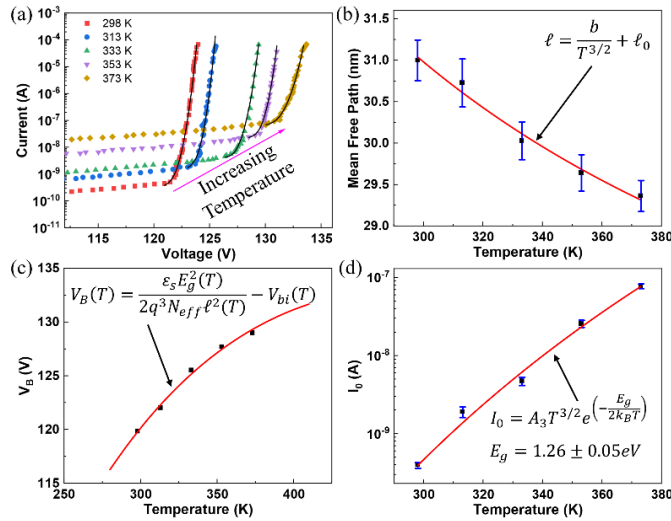


Fig. 3. (a) Avalanche current of a silicon p-n junction at different temperatures from [22]. The black solid lines represent the fitting result obtained using (4a). (b)–(d) Dependence of avalanche breakdown voltage V_B , mean-free path ℓ , and the current I_0 on temperature extracted from (a), respectively. The red solid lines in (b) and (d) are the fitting results using the equation in each subfigure. The fit parameters are $b = 3.11 \pm 0.21 \times 10^4 \text{ nm}\cdot\text{K}^{3/2}$ and $\ell_0 = 25.00 \pm 0.35 \text{ nm}$. The red solid line in (c) is the theoretical prediction of the breakdown voltage using the mean-free path extracted from (b).

and VII of SI. First, the bandgap energy was adjusted accordingly at different temperatures using empirical equations from experimental results. It directly determines the impact ionization threshold, $q\mathcal{E}\ell \geq E_g$. With increasing temperature, the reduction in bandgap energy lowers the ionization threshold. Second, the enhanced phonon scattering at higher temperatures leads to a decrease in mean-free path and carrier velocity. Consequently, free carriers become less likely to accumulate sufficient energy for impact ionization. Both reduced threshold energy and increased scattering contribute to the overall temperature dependence of breakdown behavior. Finally, higher temperature will also increase the free carrier concentration in the device, thereby altering the $n(-x_1)$ parameter in (4a).

From these fitting results, we extracted the electron mean-free path ℓ , the impact excitation coefficient γ , the breakdown voltage V_B and the thermal generation current I_0 , which are all temperature dependent as shown in Fig. 3(b)–(d), respectively. The values of the fit parameters are summarized in Table S5 in Section VII of SI. Here, we focus primarily on well-studied parameters such as the mean-free path, breakdown voltage, and carrier concentration. First, it is well known that the mean-free path is inherently dependent on the material quality, doping concentration, and temperature, etc. At room temperature, ℓ of this device is determined to be 31 nm, which is consistent with previously reported values for similar doping conditions in the range from 30 to 40 nm. Besides, ℓ is also field-dependent. Fortunately, as we discussed above, here we only focus on the avalanche region where the electric field typically ranges in a small window, e.g., $3\text{--}5 \times 10^5 \text{ V/cm}$. In this case, both the carrier saturation velocity and free carrier energy change negligibly. According to previous first-principles calculations, the variation in mean-free path is usually limited within 5–10 nm, especially when the doping concentration is beyond 10^{17} cm^{-3} . Anyway, the extracted mean-free path should be

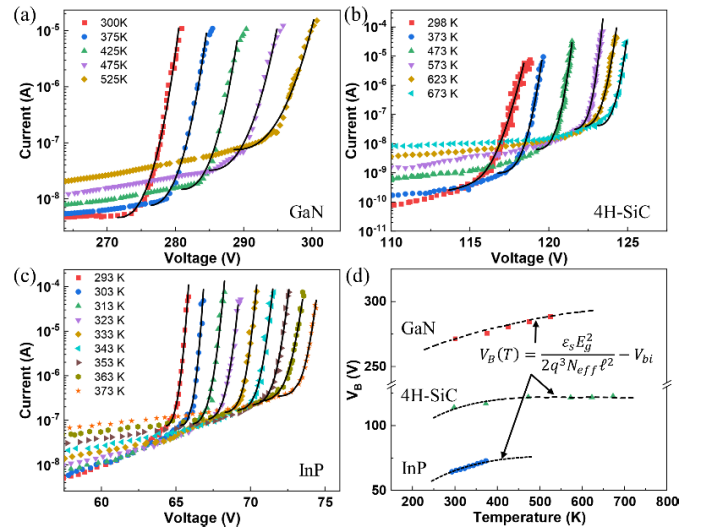


Fig. 4. (a)–(c) Avalanche current of a GaN, 4H-SiC, and InP diode at different temperatures from [26], [27], and [28]. The black solid lines represent the fitting result obtained using (4a). (d) Extracted breakdown voltage as a function of temperature from (a)–(c).

viewed as an effective parameter over the entire depletion region. Second, to strengthen the robustness of our model, we analyzed the temperature dependence of the mean-free path as follows. The increase in temperature can enhance the lattice thermal vibrations, which in turn increases carrier scattering, leading to a reduction in the mean-free path. At different temperatures, the mean-free paths we obtained are close to those obtained from first-principles calculations and theories [6], [23]. Based on previous reports [24], [25], the mean-free path ℓ can be derived to be inversely correlated with the temperature in the form of $\ell = b/(T^{3/2}) + \ell_0$, which fits the extracted mean-free path quite well, as shown in Fig. 3(b). The extracted constant b and ℓ_0 deviate from the theoretical value by a factor of a few folds (see Section VIII of SI), likely because the higher electric field in our case distorts the classical mean-free path model. Nevertheless, this agreement in both magnitude and trend provides strong support for the validity and reliability of the extracted parameters.

Given the extracted mean-free path ℓ and the theoretical expression of V_{bi} in addition to other constants, we find that the theoretical breakdown voltage V_B given in (4b) is consistent with the experimental data, shown in Fig. 3(c). Finally, the thermal generation current I_0 according to (4a) is proportional to the thermal generation in the depletion region, which is given by $G = n_i/(2\tau_0)W_{dep}$ with W_{dep} being the depletion region width, τ_0 the minority recombination lifetime and n_i the intrinsic electron concentration. Given the theoretical expression of n_i in a classical semiconductor physics textbook [6], it is not difficult to find that the current prefactor can be expressed as $I_0 = A_3 T^{3/2} e^{-E_g/(2k_B T)}$ with A_3 being a temperature-independent constant. As depicted in Fig. 3(d), the current expression fits well with the extracted temperature-dependent current, from which we extract the bandgap of the underlying semiconductor as 1.26 eV, close to the silicon bandgap 1.12 eV. Clearly, these fittings and analysis validate the analytical avalanche breakdown theory given in (4a) and (4b).

To demonstrate the universality of our analytical avalanche breakdown theory, we perform similar analysis on other widely

used semiconductor avalanche diodes including GaN, 4H-SiC and InP as shown in Fig. 4. First, it is important to note that avalanche devices based on different materials may have their distinct applications. For example, Si-based avalanche diodes are widely used as SPADs, which are usually operated at relatively small voltages and often under transient conditions. On the contrary, wide bandgap materials like GaN are commonly employed in power devices, which are usually operated at relatively high voltages and larger reverse currents, suffering from self-heating effects. We emphasize that the present work is not intended to describe the device-specific functionalities, such as photon-counting in SPADs or high-power switching in power devices. Instead, this work focuses solely on the common physical ground of these devices, i.e., the steady-state avalanche process under dark conditions, including the I-V characteristics and the avalanche breakdown voltage. External factors such as illumination, transient operation, and circuit-level effects are beyond the scope of the current framework. Accordingly, the temperature used in the analysis should be regarded as an effective device temperature, which may include contributions from self-heating. As shown in Fig. 4(a)–(c), the proposed model can fit well with all the experimental avalanche currents of these materials at different temperatures. The parameters at different temperatures used in fitting, like energy bandgap, carrier velocity, dielectric constant, etc., of these materials are listed in Section VI of SI. According to (4b), the wider the bandgap of the semiconductor, the greater the breakdown voltage V_B . This trend is consistent with many reports [29], [30], [31] and the results of InP (1.35 eV), 4H-SiC (3.27 eV), and GaN (3.47 eV) presented in Fig. 4(d). In addition, it was widely observed [26], [32], [33] that the breakdown voltage linearly increases with temperature. Indeed, a rise in temperature will intensify the thermal vibration (phonon) of crystal atoms, thereby reducing the mean-free path of carriers and increasing the breakdown voltage V_B according to (4b). However, our theoretical equation reveals that the linear increase of V_B with temperature is only valid in a limited temperature range, as shown in Figs. 3(c) and 4(d). In fact, V_B will gradually saturate in a wider range of temperatures [28], [34], [35] due to other additional temperature-dependent factors such as the semiconductor bandgap.

Another important contribution of our avalanche theory is to provide a theoretical definition of avalanche breakdown voltage V_B . Traditionally, the avalanche breakdown voltage was extracted based on empirical methods or subjective standards, such as the current threshold method, maximum curvature method, tangent extrapolation method, and reciprocal gain extrapolation method, etc. A demonstration of these methods is provided in Section IX of SI. Taking one representative of our simulation results, for example, the breakdown voltages based on the current threshold method, maximum curvature method, tangent extrapolation method, and our method are 107.6, 107.0, 105.7, and 104.6 V, respectively. Clearly, all these conventional methods tend to overestimate the breakdown voltage and fail to capture the early stage of the avalanche process. They primarily capture the regime where the reverse current has already increased substantially, rather than the true onset of avalanche multiplication. Moreover, these methods often rely on loosely defined criteria, which can lead to significant variations in the extracted values. Such definitions inherently

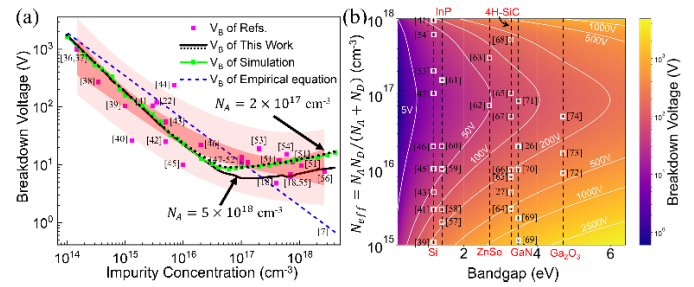


Fig. 5. (a) Avalanche breakdown voltage V_B as a function of impurity concentration in silicon. The black solid line and dots are the theoretical value of V_B in (4b). The doping concentration on one side of the p-n junction is taken as a parameter, such as $2 \times 10^{17} \text{ cm}^{-3}$ and $5 \times 10^{18} \text{ cm}^{-3}$, while the doping concentration on the other side is taken as space-independent along the X-axis. The blue dashed line is the empirical (4a). The green squares are the breakdown voltages based on TCAD simulation. The pink squares are the experimental breakdown voltages from [18], [22], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], and [56]. The deep and light pink regions are the 95% confidence and prediction areas of the experimental breakdown voltages. (b) Avalanche breakdown voltage as a function of impurity concentration and bandgap, including Si (1.12 eV) [39], [41], [43], [45], [46], [47], [51], [53], [54], InP (1.35 eV) [57], [58], [59], [60], [61], ZnSe (2.70 eV) [62], [63], 4H-SiC (3.27 eV) [27], [64], [65], [66], [67], [68], GaN (3.47 eV) [26], [69], [70], [71], and Ga₂O₃ (4.72 eV) [72], [73], [74].

involve subjective choices, and no universal standard has been established. On the contrary, the present work defines the breakdown voltage based on a physically grounded and unified criterion, as given by (4b). This definition is directly linked to fundamental material and device parameters, including the bandgap energy, dielectric constant, doping concentrations in the p-type and n-type regions, and the mean-free path. In the past, an empirical formula for V_B as a function of doping concentration and energy bandgap [7], given by $V_B = 60(E_g/1.1)^{3/2}(N_B/10^{16})^{-3/4}$, was widely adopted. According to this formula, V_B decreases as impurity concentration increases, as shown by the blue dashed line in Fig. 5(a). It predicts that V_B approaches zero at high doping concentration, which is in contradiction with many experimental reports [18], [51], [55], [56]. According to our theory (4b), V_B first decreases as the doping concentration increases and then levels off at high doping concentration due to the reduction of the mean-free path (impurities dominate scatterings). Our theoretical calculations are also very close to those obtained from the TCAD simulations. For Si-based p-n junctions, V_B reaches a theoretical minimum of 5.57 V when the n- and p-region have a doping concentration of $1.58 \times 10^{17} \text{ cm}^{-3}$ and $5 \times 10^{18} \text{ cm}^{-3}$, respectively. Ishibashi et al. [75] achieved an avalanche voltage of 5.7 V by carefully tuning the doping concentrations, which is close to the theoretical limit.

In addition, according to our theory, there should be an upper limit for V_B for a given semiconductor. Indeed, V_B increases as the effective doping concentration decreases. However, the lower limit of doping concentration is the intrinsic carrier concentration. For Si, the lower doping limit is 10^{10} cm^{-3} , which defines the maximum V_B as 10^7 V . It was reported that avalanche diodes based on high-quality single-crystal silicon with impurities and defects at a concentration of 10^{14} cm^{-3} can achieve $V_B > 1000 \text{ V}$ [36], [60]. According to our theory, there is big room for V_B to improve if the silicon quality can be further improved. In addition to doping

concentration, V_B is also dependent on the bandgap E_g . A high V_B can be readily attained in high bandgap semiconductors as shown in Fig. 5(b). Clearly, our avalanche theory also provides an important reference for designing high-performance power devices.

III. CONCLUSION

In conclusion, we have developed and validated a fundamental analytical theory for avalanche breakdown in p-n junctions based on semiconductor band theory. By modeling the ballistic acceleration and impact ionization of electrons, we derived explicit formulas for the superexponential avalanche current and the breakdown voltage. The theory successfully fits simulation results and experimental data from multiple semiconductor materials (Si, InP, 4H-SiC, and GaN) under varying temperatures, confirming its universality and correctness. The extracted physical parameters, such as the temperature-dependent mean-free path and the prefactor I_0 , align well with established semiconductor physics.

Beyond accurate fitting, this theory offers several pivotal advancements. First, it provides a precise, physics-based definition for the avalanche breakdown voltage, resolving the ambiguity inherent in previous empirical extraction methods. Second, it reveals the theoretical limits of the breakdown voltage: a nonzero minimum at high doping concentrations and a practical maximum achievable with ultrapure materials or wide bandgap semiconductors. This explains and quantitatively supports experimental observations that deviate from traditional empirical models. Finally, the model elucidates the separate contributions of thermal generation, tunneling, and avalanche currents to the total reverse-bias characteristics.

Our work thus establishes a foundational theoretical framework that directly links fundamental material properties to macroscopic avalanche device performance. It provides essential guidance for the rational design of avalanche diodes, enabling the optimization of low-voltage SPADs for integrated photonic quantum systems and the development of robust high-voltage power devices. Future work will extend this model to incorporate hole impact ionization and 2-D device geometries.

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