Mechanism for excess noise in mixed tunneling and avalanche breakdown of silicon

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We propose a mechanism to explain the excess noise observed in silicon p-n junctions biased at the onset of mixed tunneling and avalanche breakdown. Electrons tunneling into different conduction valleys are treated as separate reaction channels with different impact ionization rates, due to different initial energies, that contribute excess noise. This noise contribution is regulated by the biasing circuit to prevent runaway. We have analyzed data from past measurements and shown higher conduction valley carrier channels can adequately account for the observed excess noise. The proposed framework provides an explanation of the excess noise data without any fitting parameters. © *2010 American Institute of Physics*. [doi:10.1063/1.3457468]

In silicon p-n junctions with low breakdown voltages, a mixture of carrier tunneling and impact ionization effects appears. Their understanding and delineation are crucial in exploring devices like tunneling inductors.[1] For such inductors, although impact ionization may be needed to achieve high quality factor (Q), a too large multiplication factor (M) will create too much noise. Gaining insight into noise at the onset of mixed breakdown is, therefore, very useful.

The noise of pure impact ionization has been long studied. The theory developed by Tager[2] predicts the low frequency shot noise spectral density has a cubic dependence on M for equal electron and hole ionization rates. McIntyre[3] extended the theory for unequal rates. Subsequent experiments and simulations on avalanche photodiodes with submicron multiplication regions have shown, however, that the noise is overestimated by these theories because the nonlocal effects of dead space and rapidly varying electric field increase the coherence of the avalanche process.[4] Most of these studies have nonetheless focused on devices where the electric field is in the hundreds of kilovolt per centimeter, when only impact ionization occurs. When the field exceeds 1 MV/cm, carrier tunneling becomes significant as well. If the depletion region is very short, tunneling starts to occur before impact ionization because of the nonlocal nature of the latter process, and the combined effects of the two processes become difficult to unravel.

Lukaszek *et al.*[5,6] in fact performed systematic noise measurements on silicon p-n diodes biased at the transition from pure tunneling to mixed breakdown, where the depletion regions were around 50 nm long and the electric fields ranged from 1.5 to 2 MV/cm. In the mixed breakdown regime, the noise was shown to be significantly larger than predicted by the Tager/McIntyre theories and Lukaszek explained this by examining the avalanche onset probability. He argued that across such a thin depletion region tunneling carriers have a lower avalanche probability than the secondary carriers they generate, and this difference increases the noise. Lukaszek essentially used this probability as a fitting parameter in a statistical model he devised to match the measured data. That formulation, however, did not fit all the data equally well.

We propose an alternative explanation for the excess noise by a closer examination of the tunneling and avalanche processes under mixed breakdown. Carrier tunneling in silicon occurs between the valence band (VB) maximum and the various conduction band (CB) minima. Using the Green's function formalism,[7] tunneling to different CB minima can be treated as separate reaction channels[8] of the scattering process under the effective mass approximation. For very short distances, the impact ionization rates of different channels depend on nonstationary transport parameters, such as the concepts of dead space and carrier threshold energy.[9] The tunneling paths into different valleys, i.e., different channels, in silicon are illustrated in Fig. 1. It is evident that carriers tunneling into valleys above the CB edge have a higher initial energy and thus need to drift shorter distances to surpass the impact ionization threshold. As carriers drift, they also lose energy through phonon scattering before impact ionizing, "cascading" down the energy scale. Higher valley carriers will lose less energy on average, as shown in Fig. 1, and impart more energy to the secondary carriers they generate.

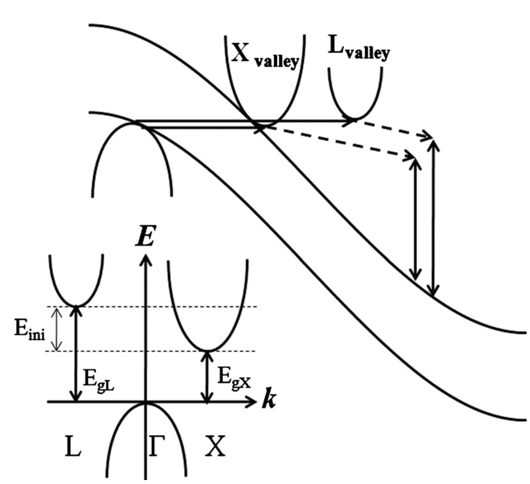

FIG. 1. Band diagram and simplified bandstructure of Si showing tunneling (solid arrows) into X and L valleys, the first and second channels in our model. Tunnel-injected carriers lose energy to phonons as they drift (dotted arrows) before impact ionizing (vertical double arrows).

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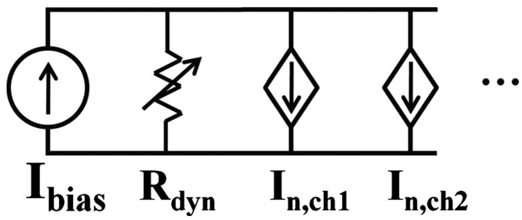

FIG. 2. Equivalent circuit for diode measurements.

As a result these carriers have a very large M. The current associated with tunneling into the lowest valley and the subsequent avalanche can be treated as the first channel. The current associated with the next valley is regarded as the second channel, and so forth. Since the tunneling rate falls off rapidly with increasing gap energy, currents from any channels above the lowest valley will be negligible even after multiplication, yet the noise they produce cannot be ignored. The Tager formula states that the avalanche noise spectral density S is $S=2qIM^3$, where I is the initiating current. Using this result as a first approximation, the noise ratio NR for each channel is

$$NR_{ch} = \frac{S_{ch}}{2qI_{ch}} = M_{ch}^3 = 1 + NR_{av}, \tag{1}$$

which is divided between the initiating tunneling current shot noise (normalized to 1) and the noise caused by avalanche, NR_{av}. If the avalanche processes of different channels are uncorrelated, the total noise can be written as the sum of the individual channel noises

$$S_{\text{total}} = \sum_n 2qI_nM_n^3. \tag{2}$$

Within this framework, the huge noise in mixed breakdown is explained by the large multiplication factors of low current, higher valley channels, as discussed later.

An important feature of this excess noise model is its self-regulating nature. Since the different channels share the same terminal voltage, the avalanche noise outputs of all higher channels are limited by the first channel, for the following reason. A simplified equivalent circuit is depicted in Fig. 2 for the noise measurement circuitry, where a current source is used to bias the diode, which is modeled as a noiseless dynamic resistance in parallel with the noise currents of each channel. Impact ionization is a "hard" breakdown process, such that M_n in Eq. (2) increases very rapidly. In a p-n junction, the terminal voltage simultaneously modulates the electric field and depletion width. Because of the high initial energy of the primary carriers in the higher valley channels, we expect M_n to be very large and effectively influenced by voltage only through depletion modulation. Conversely, the M_1 value for the first channel is relatively small, yet it is affected by both the electric field and depletion modulation. Since the regular shot noise of the first channel is affected only by the electric field that determines the tunneling rate, the first channel avalanche is the process most sensitive to terminal voltage fluctuations. If the noise current of a higher valley channel starts to increase due to runaway of its M_n, the voltage across the diode will fall and cause the first channel avalanche and noise current to decrease in a correlated fashion. This effect suppresses the total noise by regulating higher channel contributions and also offers a simple way to

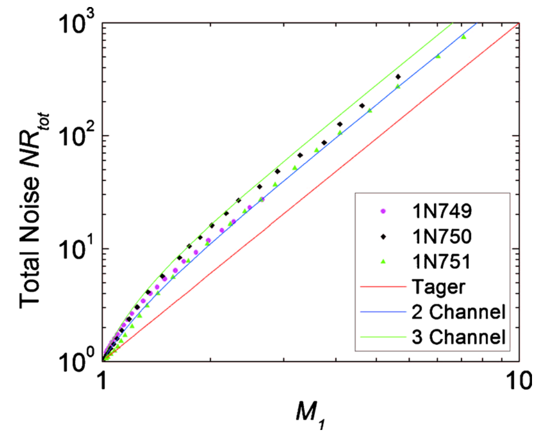

FIG. 3. (Color online) Noise ratio as a function of the first channel M_1. The 2 and 3 channel curves come from Eq. (3). 1N749, 1N750, and 1N751 are silicon p+−n diodes with n-doping of 2.85×10^{18} cm^{-3}, 2.12×10^{18} cm^{-3}, and 2.02×10^{18} cm^{-3} respectively. The measured data for these devices is taken from Ref. 5.

estimate the total noise. Since the total diode tunneling current is dominated by the first channel current, its multiplication factor M_1 is fixed by the current bias and is equal to the total M measured. In the upper limit before the regulating mechanism begins, it is reasonable to expect the avalanche noise from other channels to be the same as that of the first channel. The total noise for n channels is then the sum of their avalanche contributions plus the shot noise of the total tunneling current, which is approximately equal to that of the first channel, as follows:

$$NR_{\text{tot}} = nNR_{av1} + NR_{\text{shot}} = n(M_1^3 - 1) + 1. \tag{3}$$

The noise ratios for the two and three channel cases are plotted in Fig. 3, and compared with the Tager theory and the Lukaszek measurements. The measured data lies between the two and three channel cases with a very good fit, considering the simplicity of our assumptions. As M_1 increases from unity, the noise decreases slightly, implying an incomplete saturation of the third channel. This may be caused by the time dependence limitation of the noise at very large M, since the avalanche noise frequency is related to the inverse product of M and carrier transit time.[2,10]

To determine the details of the channel conduction, we examine the bandstructure of silicon. As illustrated in the inset of Fig. 1, tunneling is dominated by the transmission between the VB maximum and the conduction valley near the X point with band gap of 1.12 eV; this constitutes the first channel. The next valley in the CB occurs at the L point which has an energy gap of 2.1 eV,[11] which is almost twice the band gap. In the theoretical limit, electrons need to attain a threshold energy equal to the band gap to impact ionize. Since the ionization rate in silicon increases gradually with carrier energy, the effective threshold is actually "soft" and can be higher.[12] The threshold is also anisotropic but this should not make a major difference for L valley electrons.[13] The L valley electrons thus have an initial energy near the threshold level. Owing to the soft impact ionization behavior, these electrons can gain additional energy from the electric field before avalanching. As a result, the secondary carriers generated should also have a higher initial energy on average; based on these observations, the carriers associated with the L valley channel have an energy distribution with higher averaged carrier energy. This leads to a higher impact ionization rate with corresponding multiplication factor M_L. If we consider the X and L valleys as independent noise channels with tunneling currents I_X and I_L, respectively, the total noise spectral density is

$$S_{\text{total}} = 2qI_X\left(M_X^3 + \frac{I_L}{I_X}M_L^3\right). \tag{4}$$

By modeling I_L using Kane's formula[14] and the known L valley parameters, we can use the measured noise to solve for M_L. We find from Lukaszek's diodes that I_L is 7 to 12 orders of magnitude lower than I_X. Substituting the calculated I_L into Eq. (4), we estimate M_L to be in the range of several thousand and to increase slowly with voltage since it is limited by the noise feedback. Our calculation results remain in the same order of magnitude as the tunneling parameters are varied or when McIntyre's noise formula is used. Finally, we observe that direct band gaps appear in silicon[11] at symmetries Γ_{15} and $\Gamma_{2'}$ and gap energies of 3.4 eV and 4.2 eV, respectively. Though their tunneling currents are smaller than the L valley, they may form additional channels that contribute noise. These channels, however, turn off quickly because of the frequency limitation of very large avalanche.

We note that even with high values of M_L the total L valley current is still very small, which is why it has not been considered in previous studies of silicon tunneling. Because of the difficulty of directly measuring higher valley carriers, noise analysis offers an interesting perspective on this problem. It is not surprising that the effect outlined here has not been suggested before, since tunneling into higher valleys above the CB minimum is usually ignored except in materials like germanium where the direct energy gap is close to the CB edge.[15] Silicon is a good choice in this respect because its L valley is high enough above the CB minimum to show different avalanche characteristics but still make negligible current contributions. Furthermore, in most noise and impact ionization studies the electric fields are too low for higher valley tunneling to occur, which explains why large excess noise has not been observed. We note, for instance, that in Lukaszek's measurements the most lightly doped diode showed tunneling behavior but little excess noise. Complex effects are present in the very high field regime of mixed tunneling and avalanche, of which the proposed process is an example. Knowledge of the effect of material bandstructure on noise will be very useful in designing devices like p-n inductors.[1] The excess noise discussed here may also have importance and contribute to $1/f$ noise, which can affect the oscillator design of devices based on mixed breakdown.

[1] C. I. Lee and D. S. Pan, Appl. Phys. Lett. **89**, 013501 (2006).
[2] A. S. Tager, Sov. Phys. Solid State **6**, 1919 (1965).
[3] R. J. McIntyre, IEEE Trans. Electron Devices **13**, 164 (1966).
[4] See for example C. H. Tan, J. C. Clark, J. P. R. David, G. J. Rees, S. A. Plimmer, R. C. Tozer, D. C. Herbert, D. J. Robbins, W. Y. Leong, and J. Newey, Appl. Phys. Lett. **76**, 3926 (2000), and references therein.
[5] W. A. Lukaszek, A. van der Ziel, and E. R. Chenette, Solid-State Electron. **19**, 57 (1976).
[6] W. A. Lukaszek, Ph.D. thesis, University of Florida, 1974.
[7] D. R. Fredkin and G. H. Wannier, Phys. Rev. **128**, 2054 (1962).
[8] M. L. Goldberger and K. M. Watson, *Collision Theory* (Wiley, New York, 1964).
[9] G. A. Baraff, Phys. Rev. **128**, 2507 (1962).
[10] I. M. Naqvi, Solid-State Electron. **16**, 19 (1973).
[11] S. Adachi, *Handbook on Physical Properties of Semiconductors* (Kluwer, Boston, 2004), Vol. 1.
[12] E. O. Kane, Phys. Rev. **159**, 624 (1967).
[13] N. Sano and A. Yoshii, Phys. Rev. B **45**, 4171 (1992).
[14] E. O. Kane, J. Appl. Phys. **32**, 83 (1961).
[15] J. V. Morgan and E. O. Kane, Phys. Rev. Lett. **3**, 466 (1959).