Title
Cycling excitation process: An ultra efficient and quiet signal amplification mechanism in semiconductor

Journal
Applied Physics Letters, 107(5)

ISSN
0003-6951

Authors
Liu, Yu-Hsin
Yan, Lujiang
Zhang, Alex Ce
et al.

Publication Date
2015-08-03

DOI
10.1063/1.4928389

Peer reviewed

Cycling excitation process: An ultra efficient and quiet signal amplification mechanism in semiconductor

Yu-Hsin Liu, Lujiang Yan, Alex Ce Zhang, David Hall, Iftikhar Ahmad Niaz, Yuchun Zhou, L. J. Sham, and Yu-Hwa Lo

Citation: Applied Physics Letters **107**, 053505 (2015); doi: 10.1063/1.4928389
View online: http://dx.doi.org/10.1063/1.4928389
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/5?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **107**, 053505 (2015)

Cycling excitation process: An ultra efficient and quiet signal amplification mechanism in semiconductor

Yu-Hsin Liu,[1] Lujiang Yan,[2] Alex Ce Zhang,[2] David Hall,[2] Iftikhar Ahmad Niaz,[2] Yuchun Zhou,[2] L. J. Sham,[3] and Yu-Hwa Lo[1,2,a)]

[1]*Materials Science and Engineering Program, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0418, USA*

[2]*Department of Electrical and Computer Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0409, USA*

[3]*Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA*

(Received 30 April 2015; accepted 28 July 2015; published online 6 August 2015)

Signal amplification, performed by transistor amplifiers with its merit rated by the efficiency and noise characteristics, is ubiquitous in all electronic systems. Because of transistor thermal noise, an intrinsic signal amplification mechanism, impact ionization was sought after to complement the limits of transistor amplifiers. However, due to the high operation voltage (30-200 V typically), low power efficiency, limited scalability, and, above all, rapidly increasing excess noise with amplification factor, impact ionization has been out of favor for most electronic systems except for a few applications such as avalanche photodetectors and single-photon Geiger detectors. Here, we report an internal signal amplification mechanism based on the principle of the phonon-assisted cycling excitation process (CEP). Si devices using this concept show ultrahigh gain, low operation voltage, CMOS compatibility, and, above all, quantum limit noise performance that is 30 times lower than devices using impact ionization. Established on a unique physical effect of attractive properties, CEP-based devices can potentially revolutionize the fields of semiconductor electronics. *© 2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4928389]

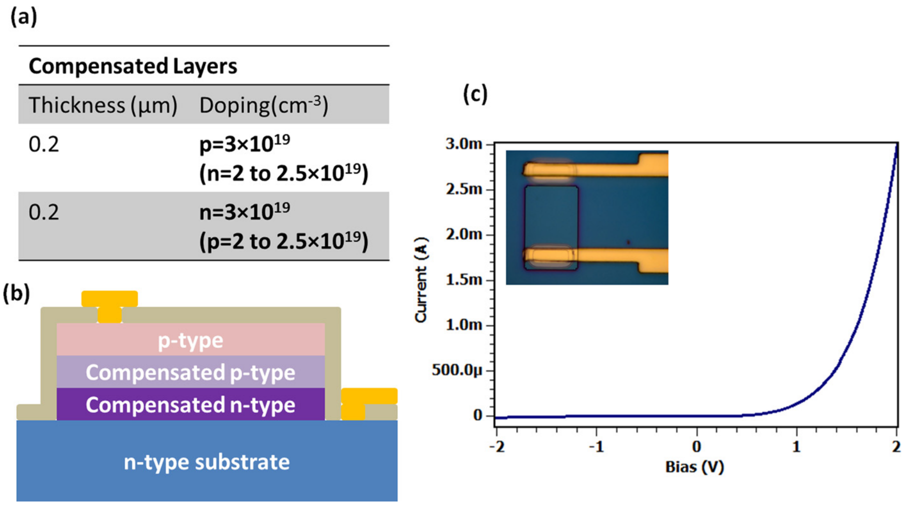
For many decades, the most sensitive systems in signal detection combine the internal (i.e., impact ionization) and external (transistor amplifier) amplification processes to achieve the highest sensitivity. This is exemplified by avalanche photoreceivers[1–11] in optical communications where an avalanche photodetector using impact ionization is concatenated with an electronic amplifier. The optimal performance is found when the quantum shot noise of the avalanche detector is equal to the thermal noise of the transistor amplifier.[12,13] However, while transistor technologies advanced rapidly, progress in the internal amplification mechanisms in semiconductors has remained stagnant. Other than impact ionization, no effective and practical internal amplification mechanism was found over the past four decades except for scientific demonstrations.[14,15] On the other hand, many fields of industry, including communications, imaging, and sensing, would benefit greatly from another intrinsic amplification process that does not have the limitations of impact ionization.

We report an intrinsic signal amplification process, Cycling Excitation Process (CEP) that is fundamentally different than the impact ionization process. We demonstrate that the CEP effect is capable of amplifying electronic signals with much greater performance than the avalanche process due to impact ionization. CEP was observed in a (partially) compensated silicon p-n junction (i.e., donors are introduced to the p-layer and acceptors are introduced to the n-layer). Here, we show CEP devices that produce the desired characteristics sought by the semiconductor community, including signal amplification by more than 4000 times at only 3 V bias and excess noise factor that is 30 times lower than today's avalanche photodetectors. We envision that CEP can be used to generate a different family of semiconductor devices as building blocks for semiconductor electronics. To demonstrate its unique characteristics and compatibility with the CMOS process, we fabricate a p-n junction Si photodetector in which the only difference of the device from a standard p-n junction detector is the incorporation of the CEP effect at the junction area. This allows the characterization of the true CEP effect without interferences from other possible side effects.

The device structure is grown by the organometallic chemical vapor deposition (OMCVD) technique to achieve precise control of the doping profile and layer thickness.[16,17] As shown in Fig. 1(a), the layer structure is the same as a conventional Si p-n junction device except that the layers near the junction have a high doping level and a doping concentration ratio ($80\% \pm 5\%$). After being patterned into a mesa structure (Fig. 1(b)) with a $35 \times 55\ \mu m^2$ optical window area shown in the optical micrograph (Fig. 1(c)), the device is tested for its photoresponse under optical (635 nm) illumination.

Although the device shows a rather typical p-n junction current-voltage characteristics in the dark condition, its photocurrent increases markedly with the reverse bias voltage, in sharp contrast with a standard p-n junction photodiode where the photoresponse remains nearly constant. At a reverse bias voltage as low as 3 V, the photoresponse gain reaches over 4000, as shown in Fig. 2(a). By contrast, for

a)ylo@ucsd.edu



(a)

Compensated Layers	
Thickness (μm)	Doping(cm^{-3})
0.2	$p=3\times10^{19}$ ($n=2$ to 2.5×10^{19})
0.2	$n=3\times10^{19}$ ($p=2$ to 2.5×10^{19})

FIG. 1. Device design and fabrication. (a) Design of the partially compensated Si p-n junction. (b) Schematic of device structure. (c) Dark I–V characteristics of the fabricated device. A typical p-n junction rectifying behavior was observed.

impact ionization to produce a gain of around 10, the p-n junction needs to be biased to over 20 V according to simulation (Silvaco software). This result demonstrates the superior characteristics of the CEP over the traditional avalanche multiplication process initiated by impact ionization. Notably, the gain of the CEP device decreases with increasing input optical power represented by the primary photocurrent in Fig. 2(a). The temperature dependence of gain shows a gain increase as the temperature increases from 140 K to 300 K (Fig. 2(c)). These results strongly suggest that phonons play significant roles in the CEP effect. The higher performance of the device with increasing temperature suggests that phonons actually assist in the amplification process rather than hinder it via phonon scattering, as discussed next.

To help understand these unique properties in Fig. 2, we have formulated the proposed physical process in rate equations (in the supplementary material[18]) and obtained an approximate expression of gain in the following equation:

$$g = G_0\left(1 - G_0^2 \cdot \frac{I_i}{I_s}\right), \quad (1)$$

where I_i is the input primary photocurrent, $I_s = \frac{qNV}{T}$ with T being the phonon absorption time in the phonon-assisted excitation process to be discussed later, N being the

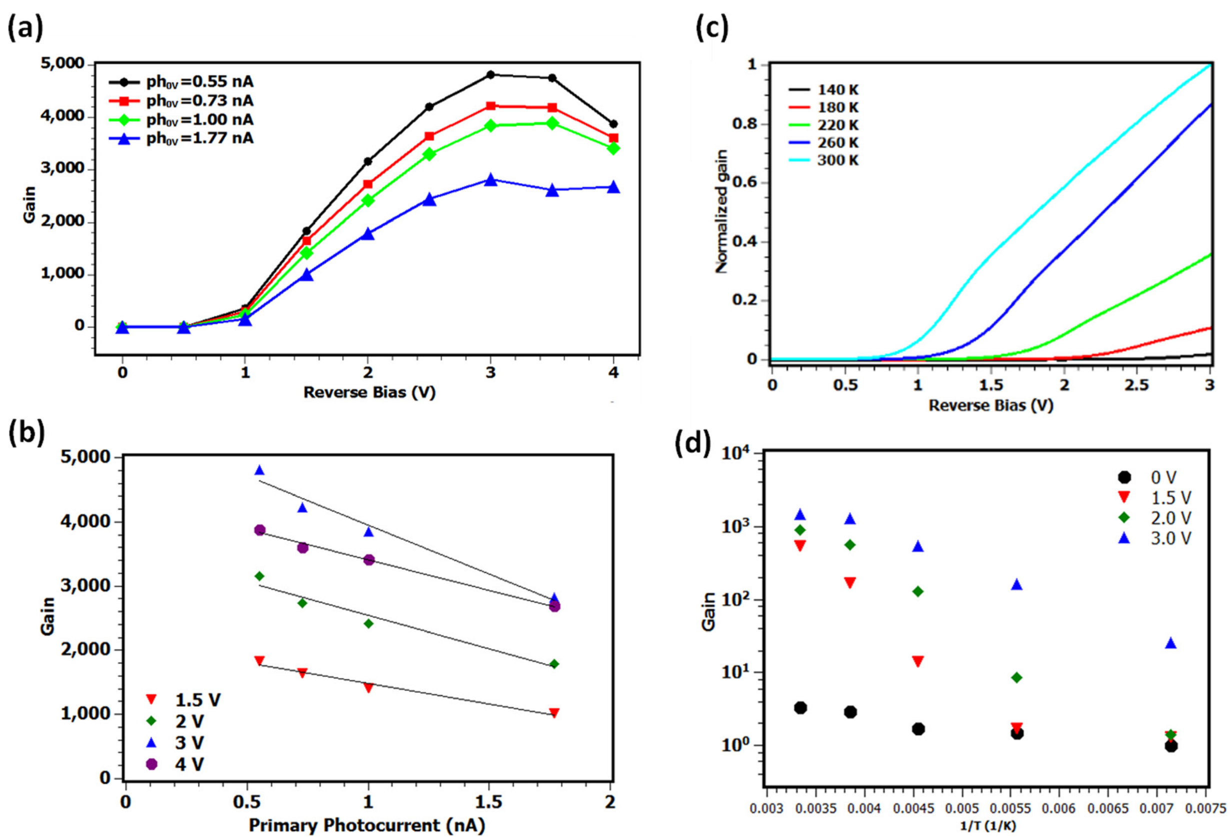


FIG. 2. Bias, input light intensity, and temperature dependence of gain. (a) and (b) Bias and input light intensity dependence of gain. The illumination (635 nm) light power is represented by the primary photocurrent at zero volt. (c) and (d) Temperature dependence of gain under 635 nm illumination in linear and Arrhenius plots. The gain values are normalized to the 300 K gain at 3 V reverse bias in (c).

compensating impurity concentration, and V being the effective volume contributing to CEP effect. G_0 is a bias-dependent parameter measuring the strength of Coulomb interaction between the energetic carrier and the charged impurity state (see supplementary material for details). Equation (1) shows the decrease in gain with increasing current injection I_i, a characteristic observed in Figs. 2(a) and 2(b). Through the gain dependence on I_s that is inversely proportional to the phonon absorption time, the model also suggests the temperature dependence of gain shown in Figs. 2(c) and 2(d).[18]

Besides high efficiency and low operation voltage, the CEP device shows particularly attractive noise characteristics. Because the device noise is primarily originated from the shot noise that is amplified with the signal, the noise characteristics are best characterized by the excess noise factor resulting from the fluctuation of the amplification factor. The excess noise factor is defined as $F = 1 + \frac{\langle \sigma_M^2 \rangle}{M^2}$, where M is the mean value and σ_M is the standard deviation of the gain.

Noise measurement was performed using the HP 8594E spectrum analyzer at 70 MHz. An optical continuous-wave laser source at 635 nm was used to illuminate the device. The device was biased with a Keithley 2400 source meter through the inductor in the bias T and connected to the noise measurement system through the DC blocking capacitor in the bias T. Considering the high noise figure of the spectrum analyzer, a low noise amplifier (LNA) with a noise figure of 1.8 dB was used to improve the system noise figure. The cascaded system noise figure was 2.76 dB, which yielded a system noise floor of −171 dBm/Hz. In order to provide impedance matching for LNA, a 50 Ω load was connected to the input of the LNA and the CEP device was connected with a parallel 50 Ω load. In this configuration, only half of the noise current generated by the device under test was measured by the system. Therefore, the actual noise power was four times the measured value, and all our data were corrected by this factor. When the noise signal was very close to the thermal noise floor, a great portion of the thermal noise would contribute to the measured value. We have subtracted the thermal noise floor from our data to obtain the actual device noise. The noise of the device was measured at various bias voltages. With known total current and gain at every bias point, the excess noise factor F was then extracted as a function of the gain M.

Figure 3 shows the measured excess noise of the CEP device and a state-of-the-art Si avalanche photodetector. Limited by the noise of the instrument itself, only the results above the instrument noise floor are included in Fig. 3. The excess noise of the state-of-the-art Si Avalanche photodiodes (APD) rises rapidly with the gain, and the measured results agree well with the McIntyre model.[19] In contrast, the CEP device shows a significantly lower excess noise than the Si APD. The excess noise factor is as low as 1.33 at a gain of 2419, which is about 30 times lower than the excess noise of state-of-the-art APD, the most sensitive semiconductor device known today. With high gain, low operation voltage, and low noise, devices built upon the CEP effect hold promise to change the paradigm of semiconductor devices.

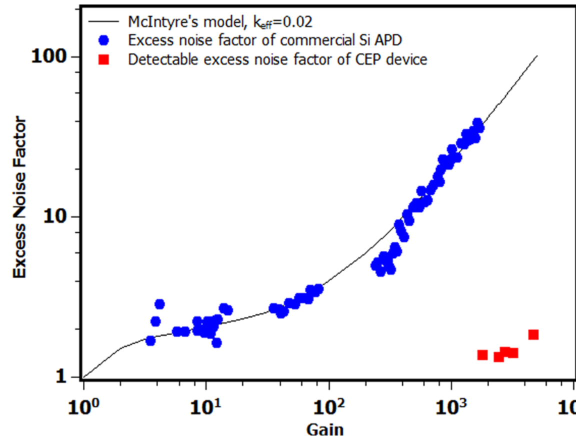


FIG. 3. Excess noise factor. The gain dependence of excess noise factor for a state-of-the-art Si APD and the CEP device. The experimental data for the Si APD are fitted with the McIntyre model (solid curve) with $K_{eff} = 0.02$, where K_{eff} is the ratio of hole and electron impact ionization coefficients. The excess noise factor of the CEP device is 1.33 at the gain of 2419, which is about 30 times lower than the excess noise of the Si APD at the same gain value.

The cycling excitation effect comes from an optically excited carrier gaining sufficient energy across the junction to excite a new electron-hole pair which provides a carrier of the opposite charge to start another pair excitation. This results in low operation voltage (i.e., 3 V bias versus 30–200 V bias for APDs), enhanced scalability and CMOS compatibility. We hypothesize that the high efficiency of the cycling excitation process is due to the strong transitions of the localized states of the compensating impurities via Coulomb interactions with the energetic carriers. These localized states relax the k-selection rule (momentum conservation),[20–22] thus enhancing the probability of new e-h pair generation via collision between the energetic carrier and the localized electrons (holes). The necessity of phonon assistance in the cycling (explained below) means that increasing reverse bias would provide a greater number of high energy carriers outstripping the available phonons, thus providing a limiting mechanism for the saturation of the gain observed in Fig. 2(a). For the cycling excitation process, phonons not only play an important role in producing the gain but also in regulating the instantaneous gain fluctuations to yield excellent noise characteristics.

As an illustration, consider an electron accelerated by a potential drop in crossing the p-n junction towards the n-region (Fig. 4(a)). In the heavily compensated n-region, the photo-generated electron acquires sufficient energy for an Auger process to excite an electron across the band gap from the acceptor. The hole left behind is susceptible to being filled by a valence band electron via phonon absorption (Fig. 4(b)). The Auger process is more probable from the acceptor than from the valence band because of the former's localized wave function, thus providing an explanation of the high excitation efficiency. The phonon assistance to provide a mobile band hole explains the gain favoring higher temperature, based on the results in Fig. 2(c). Furthermore, the band hole thus created, in crossing back the p-n junction, has a probability of a similar Auger excitation to produce an additional electron-hole pair from the compensating donors

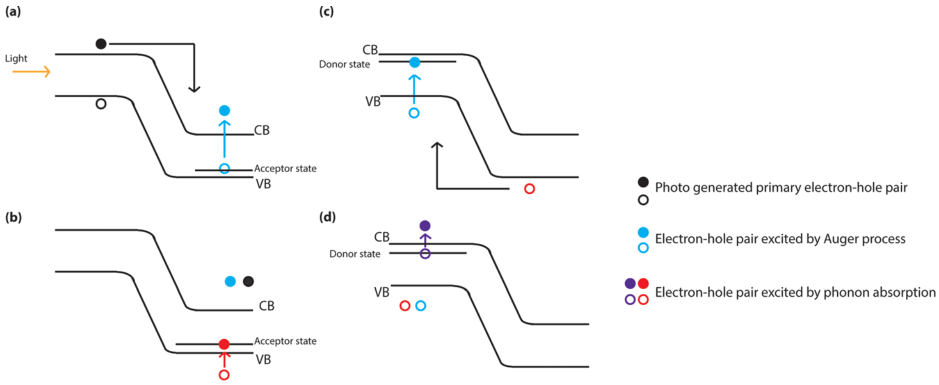


FIG. 4. Illustration of the cycling excitation process. The processes from A to D take place in sequence: (a) Primary photo generated electron excites an electron from a compensating acceptor in the n-region to the conduction band, (b) followed by a phonon-absorption process to produce a hole carrier. (c) The Auger-cum-phonon created hole may similarly add an electron-hole pair from a compensating donor in the p-region. (d) The electron carrier is created by another phonon absorption.

in the p-region (Figs. 4(c)–4(d)). The cycling process produces a series of events with geometrically decreasing probabilities, enhancing the photocurrent beyond the single electron-hole pair created by the original photon. The above stated processes can be formulated by a set of rate equations concerning electron and hole populations in the mobile and impurity states, as detailed in the supplementary material.[18]

Under the premise of ionization of a compensating impurity as essential for generating additional carriers, the gain is regulated by the state and dynamics of phonons,[23–25] thus providing a feedback mechanism to stabilize the device and suppress the device noise. Should the instantaneous gain be stronger than the mean value due to the stochastic nature of the amplification process, the limited number of local population of phonons provides a self-limiting mechanism to suppress the magnitude of gain fluctuation, thus reducing the noise. The validity of the premise of phonon-assisted generation of additional electron and hole carriers may be tested by either utilizing coherent phonons[26] as a more regulated source than thermal phonons or by replacing phonon ionization with terahertz light.

In summary, we demonstrated a heavily doped and heavily compensated silicon p-n junction device that can produce the cycling excitation process to amplify signals with unprecedented efficiency and noise characteristics. The low bias of the device, the simple and CMOS compatible fabrication process, the favorable temperature characteristics, and the ultralow noise of the amplification process make the CEP effect a highly attractive, especially promising physical mechanism for a large family of devices beyond photodiodes which we use to prove the principle. We find a reasonable explanation for the CEP effect from the use of localized impurity states introduced by the compensated structure for relaxation of momentum conservation and the use of phonons to assist the amplification process. The latter is in sharp contrast with almost all known semiconductor devices where phonons lower the device performance. For the above reasons, the CEP device shows superior performance at room temperature than at cryogenic temperature and produces record low excess noise. Although the CEP effect is demonstrated with silicon, it is reasonable to infer that the CEP effect could also be found in many other semiconductors. Our work provides the basis for future explorations in both semiconductor physics and many areas of applications.

We acknowledge the staff of the UCSD Nano3 facility for their technical support. The work was partially supported by the Office of Naval Research (N00014-15-1-2211).

[1]S. Assefa, F. Xia, and A. Vlasov, Nature **464**, 80–84 (2010).
[2]S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa, Appl. Opt. **35**, 1956–1976 (1996).
[3]M. A. Itzler, X. Jiang, B. Nyman, and K. Slomkowski, Proc. SPIE **7222**, 72221K (2009).
[4]S. Rahman, D. Hall, Z. Mei, and Y. H. Lo, Opt. Lett. **38**, 4166 (2013).
[5]S. Rahman, D. Hall, and Y. H. Lo, J. Appl. Phys. **115**, 173104 (2014).
[6]Y. Kang, H. D. Liu, M. Mose, M. Paniccia, M. Zadka, S. Litski, G. Sarid, A. Pauchard, Y. H. Kuo, H. W. Chen *et al.*, Nat. Photonics **3**, 59–63 (2009).
[7]S. Cova, M. Ghioni, A. Lotito, I. Rech, and F. Zappa, J. Mod. Opt. **51**, 1267–1288 (2004).
[8]A. Gulinatti, I. Rech, F. Panzeri, C. Cammi, P. Maccagnani, M. Ghioni, and S. Cova, J. Mod. Opt. **59**, 1489–1499 (2012).
[9]J. Cheng, S. You, S. Rahman, and Y. H. Lo, Opt. Express **19**, 15149–15154 (2011).
[10]C. Niclass, M. Gersbach, R. Henderson, L. Grant, and E. Charbon, IEEE J. Sel. Top. Quantum Electron. **13**, 863–869 (2007).
[11]H. T. Chen, J. Verbist, P. Verheyen, P. De Heyn, G. Lepage, J. De Coster, P. Absil, J. Bauwelinck, J. Van Campenhout, and G. Roelkens, Opt. Express **23**, 815–822 (2015).
[12]S. L. Chuang, *Physics of Optoelectronic Devices* (Wiley, New York, 1995).
[13]Z. Bielecki, Opto-Electron. Rev. **10**, 209–216 (2002).
[14]M. T. Trinh, R. Limpens, W. D. A. M. de Boer, J. M. Schins, L. D. A. Siebbeles, and T. Gregorkiewicz, Nat. Photonics **6**, 316–321 (2012).
[15]C. Delerue, G. Allan, J. J. H. Pijpers, and M. Bonn, Phys. Rev. B. **81**, 125306 (2010).
[16]Y. Zhou, Y. H. Liu, S. N. Rahman, D. Hall, L. J. Sham, and Y. H. Lo, Appl. Phys. Lett. **106**, 031103 (2015).
[17]Y. H. Liu, Y. Zhou, and Y. H. Lo, Appl. Phys. Lett. **103**, 041119 (2013).
[18]See supplementary material at http://dx.doi.org/10.1063/1.4928389 for details about the analytical analysis and detail fabrication process for CEP device.
[19]R. J. McIntyre, IEEE Trans. Electron Devices **ED-13**, 164–168 (1966).
[20]Y. Zhou, Y. H. Liu, J. Cheng, and Y. H. Lo, Nano Lett. **12**, 5929 (2012).
[21]P. J. Dean, J. R. Haynes, and W. F. Flood, Phys. Rev. **161**, 711–729(1967).
[22]S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (Wiley, New York, 2006).
[23]V. V. Paranjape and B. V. Paranjape, Phys. Rev. **166**, 757–762 (1968).
[24]G. Paulavičius, V. V. Mitin, and N. A. Bannov, J. Appl. Phys. **82**, 5580–5588 (1997).
[25]J. Zou and A. Balandin, J. Appl. Phys. **89**, 2932–2938 (2001).
[26]G. C. Cho, W. Kütt, and H. Kurz, Phys. Rev. Lett. **65**, 764 (1990).