Microelectronics Reliability 88–90 (2018) 568–571

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Degradation of GaN-on-GaN vertical diodes submitted to high current stress

E. Fabris[a,*], M. Meneghini[a], C. De Santi[a], Z. Hu[b], W. Li[b], K. Nomoto[b], X. Gao[c], D. Jena[d], H.G. Xing[d], G. Meneghesso[a], E. Zanoni[a]

[a] Department of Information Engineering, University of Padova, via Gradenigo 6/B, 35131, Padova, Italy
[b] School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA
[c] IQE RF LLC, Somerset, NJ 08873, USA
[d] School of Electrical and Computer Engineering, Department of Materials Science and Engineering, Kavli Institute at Cornell for Nanoscience, Cornell University, Ithaca, NY 14853, USA

ARTICLE INFO

Keywords:
Wide band gap semiconductors
Gallium nitride
pn junction
Vertical diodes
Bulk GaN substrates
Diffusion
Hydrogen
Degradation

ABSTRACT

GaN-on-GaN vertical devices are expected to find wide application in power electronics, thanks to the high current densities, the low on-resistance and the high breakdown voltage. So far, only few papers on the reliability of GaN-on-GaN vertical devices have been published in the literature. This paper investigates the degradation of GaN-on-GaN pn diodes submitted to stress at high current density. The study was carried out by means of electrical characterization and electroluminescence (EL) measurements. We demonstrate that: (i) when submitted to stress at high current density, the devices show significant changes in the electrical characteristics: an increase in on-resistance/turn-on voltage, an increase in the generation/recombination components, the creation of shunt-paths. (ii) the increase in on-resistance is strongly correlated to the decrease in the EL signal emitted by the diodes. (iii) the degradation kinetics have a square-root dependence on time, indicative of a diffusion process. The results are interpreted by considering that stress induces a diffusion of hydrogen from the highly-p-type doped surface towards the pn junction. This results in a decrease in hole concentration, due to the creation of Mg—H bonds, and in a lower hole injection. As a consequence, on-resistance increases while EL signal shows a correlated decrease.

1. Introduction

Wide-bandgap semiconductors are promising materials for the fabrication of next-generation power converters: the superior material characteristics of gallium nitride (GaN) make it suitable for high-power and high-frequency operation [1, 2]. GaN exhibits a wide bandgap, high electron mobility, and high critical breakdown field, having better figures of merit compared to Si [3].

Compared to conventional lateral components, vertical GaN devices offer the advantage of better area efficiency, a higher current/power density, and improved performance and reliability. The latter stems from the reduced defect density of GaN-on-GaN, compared to conventional GaN-on-Si devices [4–6].

GaN pn junctions are used as the basic units of vertical power devices, and are the ideal structures to study and extract preliminary information on substrate material quality, doping, defects, generation-recombination rates, avalanche, impact ionization, minority carrier lifetimes, temperature effects, and reliability [7, 8].

Only a few of papers have been published so far on stability and reliability of GaN-on-GaN devices; the aim of this paper is to contribute to the understanding of the degradation of GaN-on-GaN pn diodes stressed at high current density.

Based on combined electro–optical measurements, we analyze the physical mechanism responsible for the change in the performance of the devices, with focus on the variation of series resistance and electroluminescence (EL) signal during the stress.

2. Experimental details

Fig. 1 shows schematic cross-sectional view of the analyzed vertical GaN pn diodes. On a GaN substrate, three layers consisting of a Si-doped n GaN layer (10 µm), Mg-doped p GaN layer (0.4 µm) and Mg-doped p + GaN layer (0.02 µm) were grown. The Si-doped n-type GaN has a doping concentration of $2 \times 10^{16}\,cm^{-3}$ and an electron concentration of $2 \times 10^{16}\,cm^{-3}$, the p GaN has a Mg concentration of $1 \times 10^{19}\,cm^{-3}$ and a hole concentration of $1 \times 10^{17}\,cm^{-3}$ and the p^+ GaN has a Mg concentration of $1 \times 10^{20}\,cm^{-3}$ and a hole concentration of $1 \times 10^{18}\,cm^{-3}$. The diameter of the devices is 110 µm so the area of

* Corresponding author.
E-mail address: fabrisel@dei.unipd.it (E. Fabris).

https://doi.org/10.1016/j.microrel.2018.06.041
Received 30 May 2018; Accepted 25 June 2018

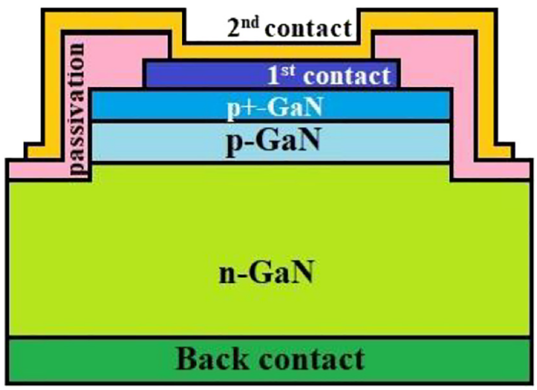

Fig. 1. Schematic cross-section of the vertical GaN pn diode.

the diodes is $9.5 \cdot 10^{-5}$ cm^2. The structures were optimized for high breakdown voltage through the use of a field plate, and the fabrication steps and the impact of the field plates are detailed in Refs. [5,7,9].

The analysis of the degradation was carried out by step-stress and constant current stress tests. Before carrying out the constant current stress measurement, the devices were submitted to a step-stress test with the aim of choosing the optimal current density to avoid instability. During the step-stress the current density applied to the pn diode was increased by 0.1 kA/cm^2 every 1800 s starting from 0.7 kA/cm^2 until failure was reached (1.2 kA/cm^2).

After this preliminary characterization, the devices were stressed at 0.7 kA/cm^2 for 36,000 s.

During stress, electrical and optical parameters of the devices were repeatedly monitored by electrical characterization and electroluminescence measurements. The analysis was carried out at room temperature.

3. Measurement results and discussion

Fig. 2 reports the behaviour of the voltage during the step-stress; the staircase represents the applied stress current. Stress was found to induce severe instabilities of the operating voltage for current levels higher than 1 kA/cm^2. For this reason, we performed the long- term stress tests at 0.7 kA/cm^2, in order to obtain gradual degradation kinetics. The results of the constant current stress are shown in Fig. 3. The voltage increases up to 22,000 s and then it starts to decrease up to 36,000 s.

The electrical and optical parameters were monitored during stress in order to better understand the physical mechanism responsible for the degradation of the pn diode.

Fig. 4 reports the changes in the electrical characteristics of the

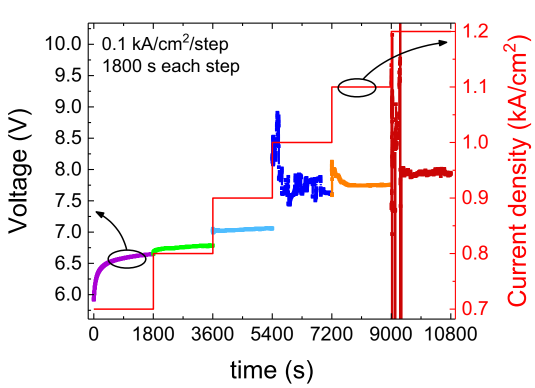

Fig. 2. Result of a step-stress measurement: the current density is increased by 0.1 kA/cm^2 every 1800 s starting from 0.7 kA/cm^2 until failure is reached (1.2 kA/cm^2).

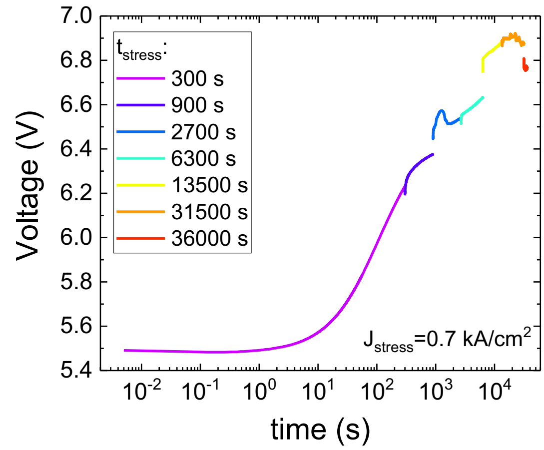

Fig. 3. Temporal variation of the voltage during constant current stress. The diode is stressed at 0.7 kA/cm^2 for 36,000 s.

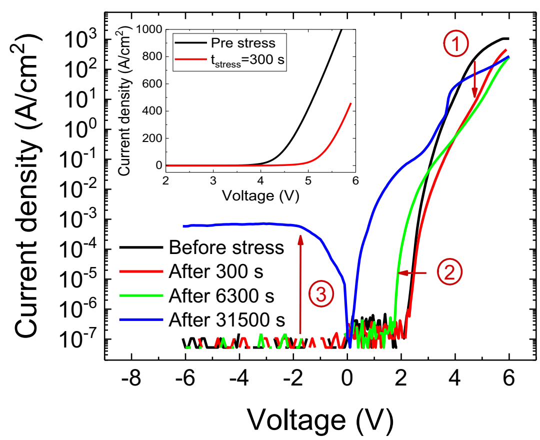

Fig. 4. Changes in the I—V curves measured during constant current stress (J_{stress} = 0.7 kA/cm^2) carried out at different stress times. We can identify three main phenomena: the decrease in the current probably due to p-type activation process (1), the increase in the current at the low forward voltage region (2) and the increase in the reverse bias leakage current(3). Inset: I—V characteristics (linear graph) measured before stress and after 300 s at 0.7 kA/cm^2.

devices at different stress times, and shows three main phenomena.

The first phenomenon (marked as (1)), is observed after 300 s of stress at high current density (0.7 kA/cm^2), and consists in an increase in turn-on voltage (inset Fig. 4). This variation may be ascribed to a degradation of the p-side of the diode, as discussed in detail in the following.

After 6300 s (mechanism (2) in Fig. 4), we observe an increase in the recombination-generation current at low forward-bias condition, which is ascribed to the increase in the conduction through deep levels (see discussion below).

The third phenomenon (mechanism (3) in Fig. 4), that is observed after 31,500 s, is the increase in the current in the reverse bias region, due to the creation of shunt-paths.

To better understand the physical origin of degradation, we measured the EL vs current characteristics (L-I curves) of the device during stress. The results are shown in Fig. 5: in the first phase of stress, we observed a gradual decrease of the optical power.

For longer times, the slope of the log-log L-I characteristics increases from nearly 1 (ideal junction) towards 1.7 (Fig. 6): this is indicative of the generation of non-radiative defects within the space-charge region [7, 10].

Remarkably, the decrease in EL is linearly correlated with the increase in on-resistance (Fig. 7), indicating that the degradation of the

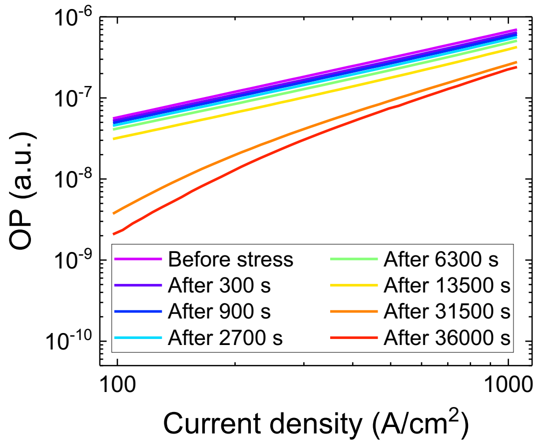

Fig. 5. L-I characteristics measured before stress and after each step of the stress at nominal current density (0.7 kA/cm^2).

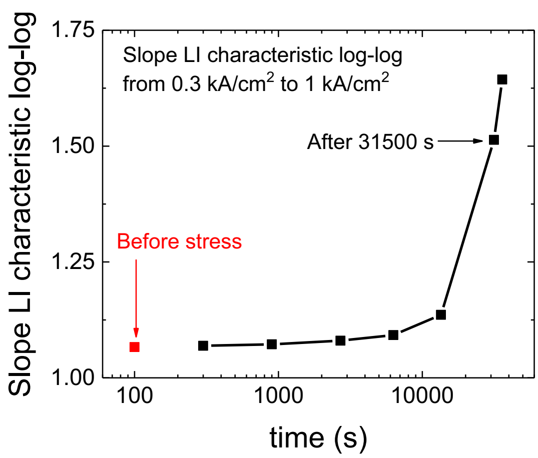

Fig. 6. Changes in the slope of the L-I characteristics (log-log graph) measured during the stress.

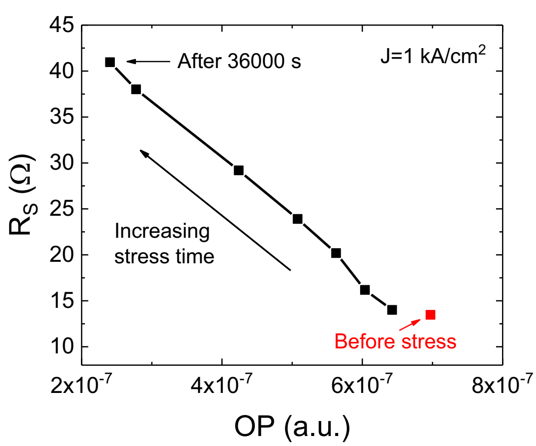

Fig. 7. Relation between the decrease in the optical power measured at 1 kA/cm^2 and the increase in the series resistance during the stress.

electrical and optical characteristics have a common origin.

This result can be explained based on the following consideration. Near the p-type contact, a high Mg-concentration is used to reduce contact resistivity [11]. During growth, a considerable amount of hydrogen is introduced within the p-GaN layer. In most cases, H-atoms create Mg—H bonds with the acceptor dopant [12, 13], thus reducing the free hole concentration.

Typically, H-concentration follows Mg-doping [14], a gradient in the concentration of H is formed between the highly-doped p-type region ([Mg] = $1 \times 10^{20}\,\mathrm{cm}^{-3}$) and the p-side of the junction ([Mg] = $1 \times 10^{19}\,\mathrm{cm}^{-3}$). During stress, the Mg—H complexes can be broken by temperature and current flow, thus leaving H interstitials; the latter can then diffuse following the concentration gradient, i.e. towards the pn junction. The temperature increase alone is too small to explain the diffusion and other degradation processes in the analyzed device, current driven diffusion mechanisms might also play a significant role.

Diffusing atoms can passivate Mg doping near the junction, through the formation of Mg—H bonds, thus decreasing the hole concentration.

A lower hole concentration results in a decrease in EL signal, and in an increase in turn-on voltage: this explains the results in Fig. 7 [10, 15].

For longer stress times, the diffusion of H can trigger a further degradation process: diffusing hydrogen atoms can fill one of the dangling bonds that form a Ga vacancy, resulting in a hydrogenated gallium vacancy. Such complexes act as efficient nonradiative centers, leading to an increase in the slope of the log-log L-I curves [16].

To verify the hypothesis that diffusion is involved in the degradation of device, the time-variation of the series resistance R_S and of the EL signal emitted by the diode at 1 kA/cm^2 are analyzed by a diffusion model that obeys the Fick's second law in one dimension (Eq. (1)):

$$N_{diff}(x, t) = N_0\, erfc\left(\frac{x}{2\sqrt{Dt}}\right) \tag{1}$$

Here, N_{diff} is the number of impurities that can be found at position x at time t, N_0 is the concentration of the impurities at the junction (that is assumed to be constant), erfc is the error function, x is the distance from the junction, D is the diffusion coefficient, and t is the stress time [17, 18].

As shown in Figs. 8 and 9, the series resistance and the EL signal (at 1 kA/cm^2) change with the square root of stress time. The square-root dependence of the stress kinetics confirms that diffusion is involved in the degradation of the diode.

The H diffusion process has already been proposed as a cause of degradation of LEDs [19] and laser diodes [17]. However, previous results were never shown the clean square-root dependence and the linear correlation between optical and electrical degradation of the homojunctions studied in this work.

4. Conclusions

In summary, with this paper we have presented an analysis of the

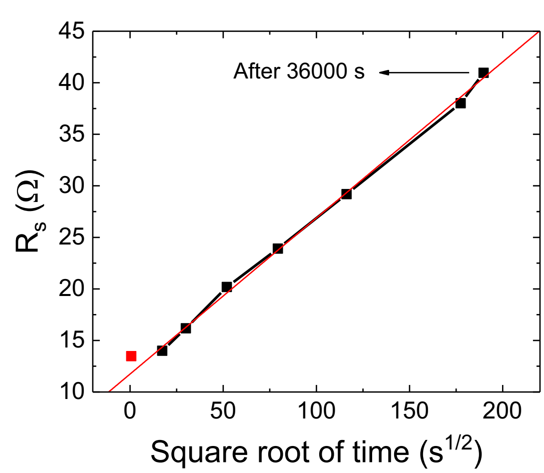

Fig. 8. Relation between the increase in the series resistance and the square root of stress time.

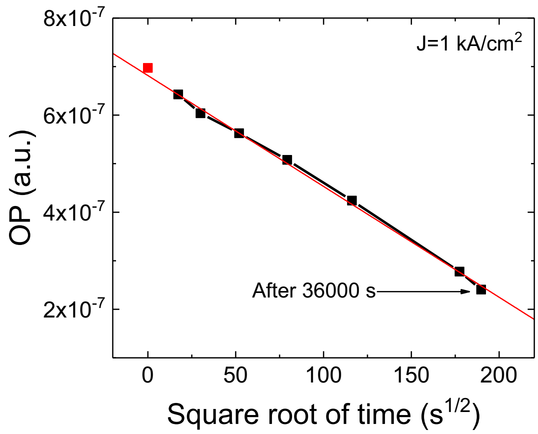

Fig. 9. Relation between the variation of the optical power measured at 1 kA/cm^2 and the square root of stress time.

physical mechanism responsible for the degradation of GaN-on-GaN pn diodes submitted to constant current stress. Stress was found to induce both an increase in turn-on voltage (and on-resistance), and a decrease in the EL signal. Both on-resistance and EL intensity vary according to the square-root of stress time, demonstrating the existence of a diffusion process.

The results are interpreted by considering that stress at high current levels favors a diffusion of hydrogen from the highly-doped p-GaN layer towards the pn junction. This results in an increase in the resistivity (due to the creation of Mg—H bonds), a lower hole injection caused by acceptor compensation, and a decrease in EL signal. A further degradation process, detected for longer stress times, is the increase in SRH recombination, possibly due to the hydrogenation of gallium vacancies.

Acknowledgements

This research activity was partly funded by project “Novel vertical GaN-devices for next generation power conversion”, NoveGaN (University of Padova), through the STARS CoG Grants call. GaN pn diodes were developed under the ARPAe SWITCHES project.

References

[1] H. Amano, et al., The 2018 GaN power electronics roadmap, J. Phys. D. Appl. Phys. 51 (February) (2018).

[2] I.C. Kizilyalli, A.P. Edwards, H. Nie, D. Disney, D. Bour, High voltage vertical GaN p-n diodes with avalanche capability, IEEE Trans. Electron Devices 60 (10) (2013) 3067–3070, https://doi.org/10.1109/TED.2013.2266664.

[3] I.C. Kizilyalli, A. Edwards, D. Bour, H. Shah, H. Nie, D. Disney, Vertical devices in bulk GaN drive diode performance to near-theoretical limits, How2PowerToday, March 2013, pp. 1–7.

[4] O. Aktas, I.C. Kizilyalli, Avalanche capability of vertical GaN p-n junctions on bulk GaN substrates, IEEE Electron Device Lett. 36 (9) (2015) 890–892, https://doi.org/10.1109/LED.2015.2456914.

[5] K. Nomoto, Z. Hu, B. Song, M. Zhu, M. Qi, R. Yan, V. Protasenko, E. Imhoff, J. Kuo, N. Kaneda, T. Mishima, T. Nakamura, D. Jena, H.G. Xing, GaN-on-GaN p-n power diodes with 3.48 kV and 0.95 mω•cm^2: A record high figure-of-merit of 12.8 GW/cm^2, Technical Digest - International Electron Devices Meeting, IEDM, vol. 2016–Febru, 2015, pp. 9.7.1–9.7.4, , https://doi.org/10.1109/IEDM.2015.7409665.

[6] Y.J. Cho, Z. Hu, K. Nomoto, H.G. Xing, D. Jena, Single-crystal N-polar GaN p-n diodes by plasma-assisted molecular beam epitaxy, Appl. Phys. Lett. 110 (25) (2017) 1–5, https://doi.org/10.1063/1.4989581.

[7] Z. Hu, K. Nomoto, B. Song, M. Zhu, M. Qi, M. Pan, X. Gao, V. Protasenko, D. Jena, H.G. Xing, Near unity ideality factor and Shockley-Read-Hall lifetime in GaN-on-GaN p-n diodes with avalanche breakdown, Appl. Phys. Lett. 107 (24) (2015), https://doi.org/10.1063/1.4937436.

[8] I.C. Kizilyalli, A.P. Edwards, O. Aktas, T. Prunty, D. Bour, Vertical power p-n diodes based on bulk GaN, IEEE Trans. Electron Devices 62 (2) (2015) 414–422, https://doi.org/10.1109/TED.2014.2360861.

[9] K. Nomoto, B. Song, Z. Hu, M. Zhu, M. Qi, N. Kaneda, T. Mishima, T. Nakamura, D. Jena, H.G. Xing, 1.7-kV and 0.55-mΩ·cm^2 GaN p-n diodes on bulk GaN substrates with avalanche capability, IEEE Electron Device Lett. 37 (2) (2016) 161–164, https://doi.org/10.1109/LED.2015.2506638.

[10] M. Meneghini, L.R. Trevisanello, G. Meneghesso, E. Zanoni, A review on the reliability of GaN-based LEDs, IEEE Trans. Device Mater. Reliab. 8 (2) (2008) 323–331, https://doi.org/10.1109/TDMR.2008.921527.

[11] O.H. Nam, K.H. Ha, J.S. Kwak, S.N. Lee, K.K. Choi, T.H. Chang, S.H. Chae, W.S. Lee, Y.J. Sung, H.S. Paek, J.H. Chae, T. Sakong, Y. Park, Recent progress of high power GaN-based violet laser diodes, Phys. Status Solidi C Conferences 2282 (7) (2003) 2278–2282, https://doi.org/10.1002/pssc.200303334.

[12] S.M. Myers, A.F. Wright, Theoretical description of h behavior in GaN p-n junctions, J. Appl. Phys. 90 (11) (2001) 5612–5622, https://doi.org/10.1063/1.1413950.

[13] C.H. Seager, S.M. Myers, A.F. Wright, D.D. Koleske, A.A. Allerman, Drift, diffusion, and trapping of hydrogen in p-type GaN, J. Appl. Phys. 92 (12) (2002) 7246–7252, https://doi.org/10.1063/1.1520719.

[14] A. Castiglia, J.F. Carlin, N. Grandjean, Role of stable and metastable Mg-H complexes in p-type GaN for cw blue laser diodes, Appl. Phys. Lett. 98 (21) (2011) 1–4, https://doi.org/10.1063/1.3593964.

[15] C. De Santi, M. Meneghini, G. Meneghesso, E. Zanoni, Degradation of InGaN laser diodes caused by temperature- and current-driven diffusion processes, Microelectron. Reliab. 64 (2016) 623–626, https://doi.org/10.1016/j.microrel.2016.07.118.

[16] C.E. Dreyer, A. Alkauskas, J.L. Lyons, J.S. Speck, C.G. Van De Walle, Gallium vacancy complexes as a cause of Shockley-Read-Hall recombination in III-nitride light emitters, Appl. Phys. Lett. 108 (14) (2016), https://doi.org/10.1063/1.4942674.

[17] K. Orita, M. Meneghini, H. Ohno, N. Trivellin, N. Ikedo, S. Takigawa, M. Yuri, T. Tanaka, E. Zanoni, G. Meneghesso, Analysis of diffusion-related gradual degradation of InGaN-based laser diodes, IEEE J. Quantum Electron. 48 (9) (2012) 1169–1176, https://doi.org/10.1109/JQE.2012.2203795.

[18] S. Tomiya, T. Hino, S. Goto, M. Takeya, M. Ikeda, Dislocation related issues in the degradation of GaN-based laser diodes, IEEE J. Sel. Top. Quantum Electron. 10 (6) (2004) 1277–1286, https://doi.org/10.1109/JSTQE.2004.837735.

[19] M. Meneghini, L.R. Trevisanello, U. Zehnder, G. Meneghesso, E. Zanoni, Reversible degradation of ohmic contacts on p-GaN for application in high-brightness LEDs, IEEE Trans. Electron Devices 54 (12) (2007) 3245–3251, https://doi.org/10.1109/TED.2007.908900.