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Temperature modes and mechanical stresses in photovoltaic converters of concentrated sunlight

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In photovoltaic converters of concentrated sunlight, the thermal flow is directed from the photoactive region ($p{-}n$ junction) to a heat-spreading basement through the substrate. The heat sink transfers the excess thermal to the environment by convection or cooled by a liquid carrier. Reducing the thickness of the substrate makes it possible to reduce the thermal resistance of the crystal and lower the operating temperature of the photoactive region. However, in this case, the mechanical stresses in it increase. This work discusses the balance between the mechanical strength of the sample and the decrease in its operating temperature.

Keywords: photovoltaic converters, heat sink, temperature regime, mechanical stress.

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Introduction

Semiconductor photovoltaic converters (PVC) are the main elements of the systems of solar energy conversion into electrical energy. In space solar cells PVC work with non-concentrated radiation, while for ground modules it is more cost effective to transform the concentrated solar radiation [1–3]. When working under conditions of intensive (at solar radiation concentration of 400−1000 units) irradiation the values of efficiency of PVC can reach 47% [4]. However, the limiting efficiency is registered at standard test conditions (25°C), while in actual systems there is always a heating of PVC. Since radiation transformation efficiency decreases with temperature increase, there is a critical problem of PVC active area temperature lowering (or stabilization) and heat removal in operating mode at persistent irradiation. The standard PVC design assumes radiation entry into the active area from the side of upper wide-band layer (window). Below active area there is usually a thin transition layer and a substrate, on which the structure epitaxy process is performed or on which the structure was transitioned at PVC production [4,5]. Design of high-efficiency multi-transition PVC assumes the use of germanium plates with thickness of up to $200\,\mu$m as the substrates.

Up to 50% of incoming solar energy, coming to PVC, is transformed into electricity and taken out into external circuit, while the remaining part is a heat, that warms up the semiconductor crystal. For operating temperature stabilization the concentrator PVC are mounted on a heat removal base [6]. Depending on the selected materials the coefficients of thermal expansion of a heat sink and semiconductor crystal can be significantly different. Since the procedure of installation usually includes PVC chip heating to high temperatures ($\sim 200^\circ$C) and the following cooling, thick substrate should provide the crystal with additional stiffness, prevent from critical stresses and defects appearing in the active area and prevent from the crystal destruction. Reduction of the substrate thickness with the corresponding simultaneous reduction of total thermal resistance, defined with its material and thickness, should be considered as an efficient method of reduction of the operating temperature of the active area and unit in general. It is obvious, that maximum effect can be reached at certain substrate thickness, that is sufficient for providing the mechanical strength and operability of PVC considering temperature modes of its lifecycle. In this work we discuss the issue of balance between reduction of the active area operating temperature (by means of substrate thickness reduction) and maintaining the sufficient mechanical strength of the semiconductor structure, mounted at heat sink.

1. Active area overheating

Thermal modes modelling and temperature determination were performed for PVC, GaAs active area of which is formed on germanium substrate. COMSOL Multiphysics software package was used for that purpose. PVC had dimensions of 3×3 mm. The substrate thickness varied from 200 to $3\,\mu$m. Copper (Cu), kovar, steel, aluminum nitride (AlN) and aluminum oxide (Al_2O_3) ceramics were considered as a material for heat sink, on which PVC was installed. Heat sink dimensions were $10 \times 12 \times 1\,\text{mm}^3$.

Irradiation distribution, formed by concentrator at PVC, was assumed as „Gaussian“ at radiation concentration multiplicity of $C = 100{-}1000$ X with radiation area size of 2.8 mm in diameter and uniform at $C = 1$ X. Solar irradiation flow density for radiation, coming to the concentrator, was assumed as $1000\,\text{W/m}^2$.

During modeling it was observed, that the presence of a solder layer $Sn_{0.62}Pb_{0.36}Ag_{0.02}$ with thickness of up to $10\,\mu$m does not make significant influence on temperature and mechanical stresses inside the semiconductor crystal (difference of the modeling results with solder and without it did not exceed 2%), therefore in the presented evaluations the contribution of solder characteristics to the appearing stresses in the semiconductor crystal was assumed negligible and was not considered. Besides, soldering the PVC on heat sink material directly is complicated, therefore heat removal plates are covered with thin copper layer. It was observed, that at copper film thickness of less than $10\,\mu$m there is no significant influence on the modeling results. Thus, hereinafter the following assumption is made: semiconductor structure is hardwired directly on heat sink, and there is a perfect thermal contact between them.

Since the thermal resistance at PVC–heat sink boundary is significantly less, than at PVC–air boundary, and the main heat flow in crystal is directed from photo-receiving surface (active area) towards the rear contact and heat sink, the active area overheating can be defined from the heat transfer equation [7]

$$q = -\chi \nabla T, \tag{1}$$

where q is heat flow, χ is thermal conductivity.

At „Gaussian" (as well as uniform) distribution of irradiation over photo-receiving surface the maximum temperature is observed in PVC center near the active area. Figure 1 shows overheating in this point as relating to room temperature (25°C) in idle mode. Thus, at solar radiation concentration multiplicity of 1000 X the difference of substrate thickness influence on the operating temperature is most apparent (Fig. 1). It should be noted, that in the presented option the copper heat sink has the maximum (for examined materials) thermal conductivity coefficient and at the same time the biggest difference of linear expansion coefficients (see the table). Examples of heat sink use (including copper ones) in the concentrator photovoltaic modules are presented in [1,2,8,9].

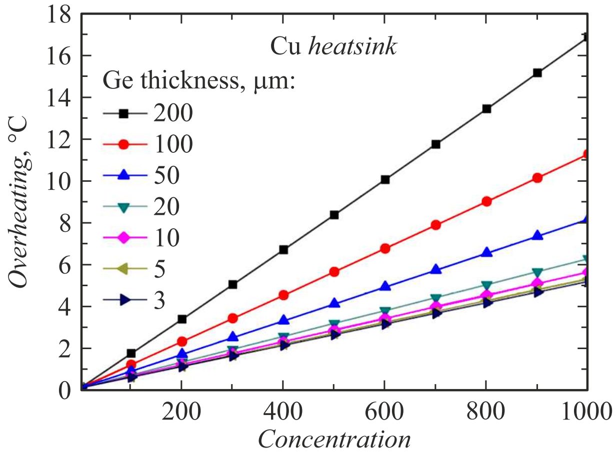

Figure 1. Overheating of PVC active area in the center as relating to the environment depending on solar radiation concentration multiplicity and change of Ge substrate thickness when using the copper heat sink with thickness of 1 mm. PVC operating mode — idle. Temperature of the heat sink rear side was maintained at environment level (25°C).

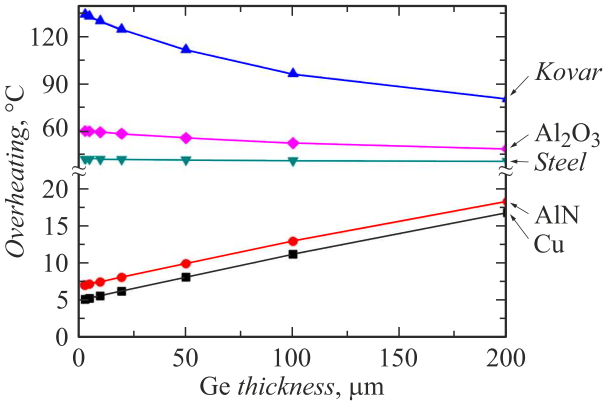

Figure 2. Overheating of PVC active area in the center as relating to the environment depending on Ge substrate thickness when using the heat sinks of copper (Cu), aluminum nitride (AlN), steel, aluminum oxide (Al_2O_3), kovar. PVC operating mode — idle. Temperature of the heat sink rear side was maintained at environment level (25°C). Concentration multiplicity $C = 1000$ X.

Efficiency of heat transfer from the active area through the substrate to the heat sink will depend on its characteristics. Thus, with decrease of germanium substrate thickness not all heat sinks can provide the conditions for reduction of PVC active area temperature (Fig. 2). For materials with lower thermal conductivity than for germanium (kovar and Al_2O_3, see the table) the reduction of semiconductor substrate thickness results in increase of temperature of p–n-junction. Thermal conductivity of steel is close to thermal conductivity of germanium, therefore with substrate thickness reduction the temperature of p–n-junction will vary insignificantly.

Application of heat sinks based on materials with thermal conductivity coefficient, exceeding the similar parameter for semiconductor germanium substrate, provides the reduction of PVC operating temperature with its thickness decrease. Thus, for instance, at solar radiation concentration multiplicity of $C = 1000$ X the temperature on the center of the active area of PVC, mounted on stabilized at $T = 25$°C heat sink of aluminum nitride ceramics, will be 43°C (for idle mode) at Ge substrate thickness of $200\,\mu$m. Temperature of similar unit with substrate thickness of $3\,\mu$m under the same conditions will be 32°C. Thus, the temperature of the active area of PVC with decreased thickness can be reduced by 11°C, that corresponds to efficiency increase by $\sim 1\%$.

2. Mechanical stresses in packaged PVC

During packaging the PVC is fixed on heat sink by means of soldering with composition of $Sn_{0.62}Pb_{0.36}Ag_{0.02}$ (solder hardening temperature is ~ 160°C). Then, the pair of „PVC–heat sink" cools to room temperature. As a result

Values of thermal conductivity and linear thermal expansion coefficient of germanium (Ge), gallium arsenide (GaAs), copper (Cu), aluminum nitride ceramics (AlN), kovar, steel, aluminum oxide ceramics (Al_2O_3) at room temperature [10–23]

Material	Ge	GaAs	Cu	AlN	Kovar	Steel	Al_2O_3
Thermal conductivity (χ),W/(m·K)	61	33	401	287	14	47	35
Thermal expansion coefficient $\times 10^{-6}, K^{-1}$	6.1	6	16.5	5.3	6.2	13.8	5.6

of such process operation implementation the mechanical stresses can appear in PVC semiconductor structure due to difference of linear expansion (compression) coefficients of substrate and heat sink material. Therefore, to prevent from damage of PVC active area layers due to mechanical stresses, initiated from the side of contact area of PVC and heat sink, the substrate thickness should remain significant, that, as was discussed above, will prevent from excessive heat removal from $p-n$-junction and result in overall heating of PVC.

Despite the lateral sizes (along X and Y axes) of the modelled object significantly exceeded the vertical size (along Z axis), according to preliminary evaluation the deformations in all directions were insignificant. Therefore, during calculations it was assumed, that the examined object is subject to small deformation. In this case the model of elastic solid body deformation can be used [24]. Calculation results are presented as mechanical von Mises stresses [25]. Such representation allows to directly compare them with the examined materials yield stress. The modeling was performed using COMSOL Multiphysics mathematical software package based on calculations, presented in [26,27].

Calculations of stresses, appearing in PVC structures (3 × 3 mm) with germanium substrate, when using various heat sinks (copper, kovar, steel, Al_2O_3 and AlN ceramics), were performed. Environment temperature was assumed as 25°C. Thus, the temperature difference during the process procedure of PVC soldering on the heat sink and „cold“ state was 135°C. In this work we examined the models with minimum sampling rate of 1 μm on Z axis and 10 μm on X and Y axes, that was sufficient for making the illustrative picture of the mechanical stresses.

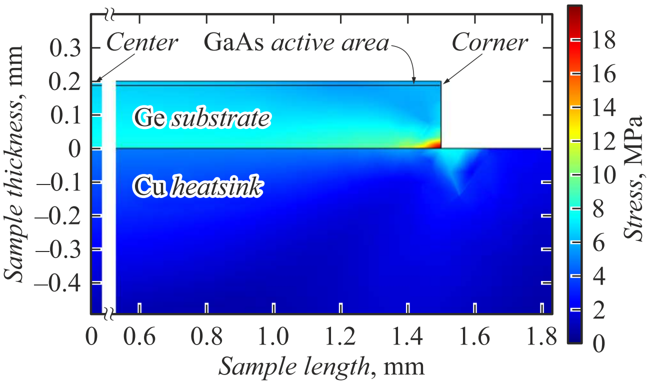

Figure 3. Typical distribution of stresses inside the unit with 200 μm Ge substrate, mounted on copper heat sink. Data are presented for the vertical section, passing through the unit center and side face center.

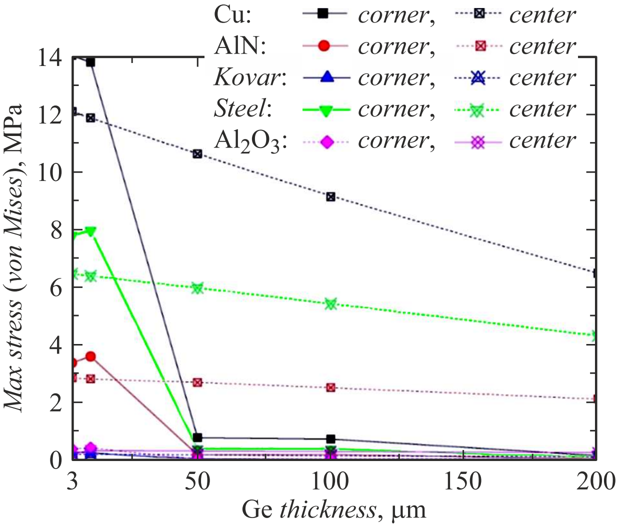

Figure 4. Dependence of stresses (von Mises) at the boundary of the active area and substrate on the corner of crystal (solid lines) and in the center of crystal (dashed lines) on substrate thickness when using heat sinks of the following materials: copper (Cu), kovar, steel, aluminum nitride (AlN) and aluminum oxide (Al_2O_3) ceramics.

Figure 3 illustrates the typical distribution of stresses in the examined PVC, fixed on the copper heat sink. Results are presented for the vertical section, passing through PVC center and its side face center (points [0, 0] and [0, 1.5]). Stress in the semiconductor structure is observed over the whole contact with the heat sink, while near PVC edge the areas with increased stress appear. For all heat sink materials the design stresses in the substrate did not exceed the yield stress of germanium [28]. With reduction of Ge substrate thickness the active area becomes closer to PVC–heat sink contact. In this case at significant mismatch of thermal expansion coefficients of semiconductor structure and heat sink (copper, steel, Al_2O_3 ceramics (see the table)) the increased mechanical stresses can also spread to the active area material (GaAs layer).

Figure 4 shows the dependence of stresses at substrate–active area boundary on germanium substrate thickness for heat sink materials: copper, kovar, steel, Al_2O_3 and AlN ceramics. Values of stresses on PVC corner and in its center are presented (points are showed in Fig. 3 as „corner" and „center"). The general trend in stresses distribution is that the areas with increased values are located near crystal corners near substrate–heat sink boundary. With increased distance from the heat sink the stresses on corners relax faster, than in the structure center. Thus, at low substrate thickness (less than $10\,\mu$m) the area of increased stress on corners of the semiconductor structure reaches the active area for all heat sink options. Especially vivid this effect appears for heat sinks of copper, steel and AlN ceramics, since the thermal expansion coefficients of these materials significantly differ from germanium (see the table). At substrate thickness of more than $50\,\mu$m the stresses on corners dramatically reduced. In the center the stress reduced linearly with the substrate thickness. Thus, at substrate thickness of more than $50\,\mu$m, it was bigger than on the corner.

In units with heat sinks of materials with linear expansion coefficient, close to germanium, the lowest values of the stress in the active area are observed: 0.3 MPa for kovar and 0.4 MPa for Al_2O_3. However, their thermal conductivity is lower than for germanium, therefore their use for the heat sink is possible only for units with thick substrate under special conditions.

For PVC on copper heat sink the most significant structural stresses, reaching the active area, are observed. In this case PVC use with substrate thickness of less than $100\,\mu$m is not allowed, since the appearing stresses are higher than yield stress of GaAs active area material (10 MPa [29]). It should also be noted, that during packaging the additional mechanical impacts can appear at PVC from the active area side, for instance at contacting with a measuring probe or installation (flanging) of the upper current drainage bus. For PVC resistance to such impacts it is necessary to provide a „safety buffer", optimizing the thickness of germanium substrate.

When using the heat sink of AlN ceramics, similar to copper in terms of thermal conductivity, the maximum stress in the active area is 3.6 MPa in the crystal corner and 2.9 MPa in the center. Maximum stress difference in structures with thin and standard substrate does not exceed 1.5 MPa, that allows to provide the favorable temperature mode for PVC with reduced thickness without degradation of photovoltaic characteristics due to mechanical stresses.

Conclusion

The options of reduction of the operating temperature of GaAs p–n-junction into PVC with germanium substrate with reduced thickness during operation under conditions of the concentrated solar radiation transformation are examined in the work. The applied packaging (soldering) procedure results in appearance of mechanical stresses, initiated from the side of PVC and heat sink contact area, therefore the process of thickness reduction along with operating temperature decrease results in increase of structural stresses in PVC. Such stresses can propagate over the semiconductor material, increase and reach PVC active area, lowering its efficiency. Therefore, the application of heat sinks based on materials with thermal conductivity higher than for germanium, always reduces the operating temperature of PVC with substrate with reduced thickness.

It was shown, that when using the copper heat sink under radiation conditions of $C = 1000\,\text{X}$ the calculated temperature of GaAs active area decreases from 41 to 30°C when Ge substrate thickness is reduced from 200 to $3\,\mu$m, but at the same time the mechanical stresses appear in the active area, exceeding its material yield stress, that can result in destruction of units with thickness of less than $100\,\mu$m.

The most prospective material for heat sink in terms of the active area operating temperature lowering and decrease of mechanical stresses in it is AlN ceramics. With substrate thickness decrease from 200 to $3\,\mu$m the maximum stresses in soldered PVC increase from 2 to 3.6 MPa, that is significantly less than yield stress of the active area material — GaAs (10 MPa). At the same time, the active area temperature decrease from 43 to 32°C is expected in idle mode or from 36 to 28°C in the optimum load mode at concentration multiplicity of $C = 1000\,\text{X}$, that is equivalent to efficiency increase by about 1% [30,31].

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.V. Chekalin, A.V. Andreeva, N.Yu. Daviduk, N.S. Potapovich, N.A. Sadchikov, V.M. Andreev, D.A. Malevsky. ZhTF, **91** (6), 915 (2021) (in Russian). DOI: 10.21883 JTF.2021.06.50859.314-20

[2] M. Steiner, A. Bösch, A. Dilger, F. Dimroth, T. Dörsam, M. Muller, T. Hornung, G. Siefer, M. Wiesenfarth, A.W. Bett. Prog. Photovolt: Res. Appl., **23** (10),1323 (2014). DOI: 10.1002/pip.2568

[3] N.A. Pakhanov, V.M. Andreev, M.Z. Shvarts, O.P. Pchelyakov. Optoelectronics, Instrumentation and Data Processing, **54**, 187 (2018). DOI: 10.3103 S8756699018020115

[4] J.F. Geisz, R.M. France, K.L. Schulte, M.A. Steiner, A.G. Norman, H.L. Guthrey, M.R. Young, T. Song, T. Moriarty. Nature Energy, **5**, 326 (2020). DOI: 10.1038 s41560-020-0598-5

[5] X. Zhang, J. Hu, Y. Wu, F. Lu. J. Phys. D: Appl. Phys., **42**, 145401 (2009). DOI: 10.1088/0022-3727/42/14/145401

[6] N.Yu. Daviduk, A.V. Andreeva, D.A. Malevsky, P.V. Pokrovsky, N.A. Sadchikov, A.V. Chekalin, V.M. Andreev. Tech. Phys. Lett., **46**, 436 (2020). DOI: 10.1134/S1063785020050041 [N.Yu. Daviduk, A.V. Andreeva, D.A. Malevsky, P.V. Pokrovsky, N.A. Sadchikov, A.V. Chekalin, V.M. Andreev. Tech. Phys. Lett., **46**, 436 (2020). DOI: 10.1134/S1063785020050041]

[7] L.D. Landau, E.M. Lifshitz. *Theory of Elasticity* (3rd ed.) (Elsevier, 1986), v. 7, Ch. V, p. 152. DOI: 10.1063/1.3057037

[8] A.V. Andreeva, N.Yu. Daviduk, D.A. Malevsky, A.N. Panchak, N.A. Sadchikov, A.V. Chekalin. FTP, **52**, 3 (2018) (in Russian). DOI: 10.21883 JTF.2021.02.50365.155-20

[9] G. Peharz, J.P.F. Rodríguez, G. Siefer, A.W. Bett. Prog. Photovolt: Res. Appl., **19**, 54 (2011). DOI: 10.1002 pip.987

[10] A.S. Okhotin, A.S. Pushkarskii, V.V. Gorbachev. *Thermophysical Properties of Semiconductors* (Atom, Publ. House, M., 1972)

[11] J.S. Blakemore. J. Appl. Phys., **53** (10), 123 (1982). DOI: 10.1063/1.331665

[12] M. White, J. Gran, N. Tomlin, J. Lehman. Metrologia, **51**, S245 (2014). DOI: 10.1088/0026-1394/51/6/S245

[13] G.A. Slack, R.A. Tanzilli, R.O. Pohl, J.W. Vandersande. J. Phys. Chem. Sol., **48** (7), 641 (1987). DOI: 10.1016/0022-3697(87)90153-3

[14] M. Bukhari, M.S.J. Hashmi, D. Brabazon. In *The 2nd International Malaysia–Ireland Joint Symposium on Engineering*, Science and Business (IMiEJS), 2012 At: Putra World Trade Centre, Kuala Lumpur, Malaysia.

[15] E. Ranjbarnodeh, S. Serajzadeh, A.H. Kokabi, A. Fischer. J. Mater. Sci., **46**, 3225 (2011). DOI: 10.1007/s10853-010-5207-8

[16] W. Martienssen, H. Warlimont *Springer handbook of Condensed Matter and Materials Data* (Springer, Berlin, 2005), p. 431. DOI: 10.1007/3-540-30437-1

[17] S.I. Novikova. Sov. Phys. Sol. State, **2** (1),37 (1960).

[18] S.I. Novikova. Sov. Phys. Sol. State, **3** (1),129 (1961).

[19] D. Minakov, P. Levashov. Phys. Rev. B., **92**, 224102 (2015). DOI:10.1103/PhysRevB.92.224102

[20] G.A. Slack, S.F. Bartram. J. Appl. Phys., **46** (1), 89 (1975). DOI: 10.1063/1.321373

[21] L. Del Castillo, D. Schatzel, C. Weber, T. Hatake, M. Mojarradi, E.A. Kolawa. *In Proc. 4th Int. Planetary Probe Workshop*, (2006).

[22] G. Sun, Z. Chen, Z. Liu. J. Mater. in Civil Engineer., **23**, 1017, (2011). DOI: 10.1061/(ASCE)MT.1943-5533.0000271

[23] Y. Wang, J.J. Wang, W.Y. Wang, Z. Mei, S. Shang, L. Chen, Z. Liu. J. Physics-Condensed Matter, **22**, 202201 (2010). DOI: 10.1088/0953-8984/22/20/202201

[24] L.D. Landau, E.M. Lifshitz. *Theory of Elasticity* (3rd ed.) (Elsevier, 1986), v. 7, Ch. I, p. 2. DOI: 10.1063/1.3057037

[25] R.M. Jones. *Deformation Theory of Plasticity* (Bull Ridge Corporation, 2009), Section 4.5.6, p. 151. ISBN: 978-0-9787223-1-9

[26] Y. Deng, S. Tang, D. Tung. *2018 IEEE International Conference on Applied System Invention* (ICASI), (Chiba, Japan, 2018), p. 1149-1151. DOI: 10.1109/ICASI.2018.8394487

[27] M. Vajdi, F. Moghanlou, F. Sharifian Jazi, M. Shahedi Asl, M. Shokouhimehr. J. Composites and Compounds, **2** (2), 35 (2020). DOI: 10.29252/jcc.2.1.5

[28] Yu.V. Milman, I.V. Gridneva, A.A. Golubenk. Sci. Sinter., **39**, 67 (2007). DOI: 10.2298/SOS0701067M

[29] I. Yonenaga, K. Sumino. J. Appl. Phys., **71**, 4249 (1992). DOI: 10.1063/1.350805

[30] C. Algora, I. Rey-Stolle. *Handbook of Concentrator Photovoltaic Technology* (Willey, United Kingdom, 2016), p. 264. DOI: 10.1002/9781118755655

[31] E.F. Fernández, G. Siefer, M. Schachtner, A.J. García Loureiro, P. Pérez-Higueras. AIP Conf. Proceed., **1477**, 189 (2012). DOI:10.1063/1.4753865