DEVELOPING A MINI-IMPACT SYSTEM FOR MEASURING SILICON WAFER’S ELASTODYNAMIC RESPONSE

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ABSTRACT

The purpose of this work is to study the dynamic mechanical response of silicon wafer subjected to low-velocity impact loading. Transient finite element analysis was utilized to obtain the numerical simulated result and was used to check against the experimental findings. Good relationship between each other was observed. A pair of polysilicon microsensors manufactured by the micro-fabrication technique was directly fabricated on the surface of silicon wafer so as to detect the impact induced dynamic strain. A series of low-velocity impact tests utilizing the home-made drop-weight mini-tower tester was conducted. These test results were used to examine the accuracy and adequacy of the current micro strain sensors for stress wave propagation measurements. It is concluded that the difference between the present measured wave speed and the one-dimensional longitudinal wave speed under conditions of plane strain \( C_{L}^{2} = \frac{E}{\rho (1 - \nu)^{2}} \) were determined to be within 5.6% for the present low-speed impact problem. A maximum of 10.9% deviation between the test determined elastic modulus and a reference value (16) of 130 GPa was found based on a series of impact test results. In addition, a difference of 2% error was reported when we compared the test detected peak stress value after impact initiated (before wave is reflected from the boundary) and the corresponding numerical simulated response.

Keywords: Microsensors, Silicon, Impact response, MEMS, Strain sensor, Dynamic elastic property.

1. INTRODUCTION

The electronics revolution in the 1960s started the miniaturization of many appliances such as televisions, radios, camcorders, computers, etc. These products become quite natural and rather useful in our daily life. Recently, the miniaturization of non-IC hardware, such as biological, mechanical and physical sensors along with signal processing instruments, becomes heavily emphasized, and a number of microfabricated sensors/devices were introduced. Microsensors have been widely adopted in automotive industry, such as temperature sensors (to detect inside and outside temperature of vehicle), accelerometer (for air-bag release), light sensors (to turn on the lights), and so on (1,2). Furthermore, microfabricated sensors and instruments in biomedical applications and miniaturization in analytical equipments are also introduced to the market. These tiny scale sensors have been proven to be size miniaturizing, material saving, and they also possess a capability to integrate with signal processing and controlling circuitry. In addition, the cost of micromachined sensors is expected to be price competitive, although the microfabrication cost seems to be higher at the present stage.

In this study, the piezoresistive type miniature strain gages made of polysilicon were used to detect dynamic impact response of specimen. A number of previously reported works related to this study is summarized below. Pfann and Thurston (3) explained that piezoresistivity is based on a quantum mechanical description of crystal lattice strain effects on the conductivity of electrons and holes as a function of lattice direction. After the crystalline silicon is properly doped, temperature and force exerted on the crystal lattice can affect the piezoresistance. A number of published works can aid us to design and fabricate piezoresistive type miniature strain gages. Obermeier and Kopystynks (4) reported the effect of doping concentration on the resistivity, temperature coefficient of resistance and gauge factors. The possibilities for temperature compensation and the trimming capability are the most important advantages of polysilicon as opposed to monocrystalline silicon. Gridchin, Lubinsky and Sarina (5) presented a simple theoretical model for calculating the longitudinal, transverse and shear gauge factors of highly doped
polycrystalline silicon films. Their theory is in quantitatively reasonable agreement with test findings and seems helpful for transducer designers. In 1997, Laghla, et al. (6) presented results on the electrical and optical properties of thin layers made of polysilicon obtained by low pressure chemical vapor deposition (LPCVD) method. These layers were either undoped or in situ doped with boron or phosphorus. The resistivity of doped polysilicon film is determined experimentally. Recently, Bromley, Howell and Jensen (7) used the simple technical beam theory to relate the failure strain to the failure tip deflection of a cantilever beam. Experiments were conducted and it was recommended that the nominal allowable stress and strain are 930MPa and 0.0055, respectively.

Although the initial attraction of polysilicon was the ability to deposit semiconductor layers on a wide range of substrates, it has been applied as the strain sensors based on piezoresistive effect. The grain size of polysilicon is highly dependent on processing and therefore a wide range of electrical and mechanical properties can be achieved (8). It is noted that the theoretical gage factor of the polysilicon strain sensors is ranged from 25 to 40 and which is much higher than that of a commercial metal foil strain gage.

In the area of the characterization of material mechanical properties under dynamic impact response, numerous research studies have been reported in the past (9) ~ (13). However, using polysilicon micro sensor to detect impact response of a mini-scaled beam structure has not been reported. In the present work, a miniature strain gauge was designed and produced using the microfabrication techniques in order to detect the transient dynamic response of a mini-structure subjected to low energy impact loading. The measured dynamic signals can aid us to determine the elastic wave speed and dynamic elastic property of the wafer material. If we build these miniature strain gages on a semiconductor device at proper locations, the techniques gained from this research work could assist us to conduct a direct tracing of the thermo-mechanical dynamic response and/or to monitor the electric/mechanical service conditions for any device (e.g. the electronic printing circuit board or semiconductor chip) in question. With the use of microstrain gage reported here, it is furthermore expected that the stress intensity factor and the health condition of a specific device could be real time dynamically observed.

2. DESIGN OF MICRO STRAIN GAUGE

Microfabrication technique is adopted in the present work to make tiny strain gauges made of polysilicon material. The microsensor is fabricated on the silicon substrate with an insulating thin layer in between. The size of present micro strain gauge is designed to be 650 by 1,050µm with a layer thickness of 0.5µm when a plastic mask is used for the UV lithography process. Notice that the sensor size can be furthermore reduced if a precision glass mask is adopted in the process of fabrication. Using the LPCVD method, polysilicon was deposited on the surface of a (100) 4 inch diameter single-surface polished silicon wafer. Boron doping was then applied to the surface by using an ion implantation machine. Doped polysilicon needs to be annealed in an oven at a temperature of 950°C for approximately 30min, so that the disrupted silicon crystal structure due to implantation process can be reconstructed. Keep in mind that if the annealing process is not properly taken cared of, the sensor would not be able to function properly due to the presence of high resistance.

Obermeier and Kopystynski reported (4) the relative resistance change of boron-doped LPCVD polysilicon resistors with the implantation dose as the varying parameter over the temperature ranging from −60 to +160°C. The resistance between 0 to 40°C can be expressed as

\[ R(T) = R_0 \exp[\alpha_R(T - 20°C)] \]  

where \( \alpha_R = \frac{1}{R_0} \left( \frac{dR(T)}{dT} \right)_{T=20°C} \) is the temperature coefficient at 20°C. In order to minimize the temperature effect of the resistance, i.e. the temperature coefficient \( \alpha_R \) should be chosen to be very close to zero, the doping concentration is set to be \( 2 \times 10^{19} \) to \( 5 \times 10^{19} \) cm\(^{-3} \). Since the gage factor \( (G) \) of a sensor is an important parameter to indicate the sensitivity between strain and the relative resistance change. The longitudinal gage factor \( (G_L) \) of the LPCVD polysilicon boron doped sensor material was reported to be 27 to 29 when the doping concentration is \( 2 \times 10^{19} \) to \( 5 \times 10^{19} \) cm\(^{-3} \). However, the actual gage factor would be affected by the variation of LPCVD polysilicon material property, anneal process, doping conditions, etc.

In this study, the doping concentration is selected to be \( 3 \times 10^{19} \) cm\(^{-3} \). At this concentration, the temperature coefficient \( (\alpha_R) \) is approximately zero (4) and a resistivity of \( 1.3 \times 10^{-2} \)Ω·cm for the doped polysilicon sensor is predicted based on the relationship between doping concentrations and resistivity (4).

For an IC resistor design, the resistance of a rectangular block of uniform doped material can be written as

\[ R = \rho \frac{L}{A} \]  

where \( L \) and \( A \) are the length and cross-sectional area of the block, respectively, and \( \rho \) is material resistivity. If the width and thickness of the block are represented by \( W \) and \( t \), respectively, Eq. (2) can be rewritten as

\[ R = (\rho / t)(L/W) = R_s(L/W) \]  

where \( R_s \) is the sheet resistance. In general, a circuit designer can use the sheet resistance and the number of “squares” of the resistor to calculate its corresponding
resistance (14). Since the resistivity ($\rho$) for the present application is designed to be $1.3 \times 10^{-2} \Omega\cdot cm$ the 0.5µm thick sensor’s sheet resistance ($R_s$) is determined to be 260Ω. Subsequently, the calculated resistance of the present sensor is computed to be 7,290Ω based on the geometry of the boron doped polysilicon sensor given in Fig. 1. A detailed description for calculating the sheet resistance and sensor resistance is referred to Ref. [15]. Notice that the line width of the present sensor is 100µm and there is a gap of 50µm between lines as shown in Fig. 1. In addition, the sensor’s width and length are 650 and 1,050µm, respectively, and the gage length is 850µm.

3. FABRICATION OF THE MINI-TARGET BAR WITH MICROSENSORS INSTALLED

The impact response of a rectangular bar with a length and width of 6.9cm and 0.375cm, respectively, is studied here. In addition, the thickness of this target bar is 500µm. This bar specimen was cut from a 4 in. diameter circular single side polished silicon wafer. Two micro strain gages were directly fabricated on the surface of the target specimen, as shown in Fig. 2. Notice that the target bar is clamped on one end, while the other end is free of constraint. These two boron-doped LPCVD polysilicon micro strain sensors were installed 1.38cm and 5.565cm from the free end. The distance between these two micro strain sensors is 4.184cm.

The (100) 4 in. diameter silicon wafer was used to as the substrate material. A series of microfabrication procedures were adopted to make the micro strain gages on the substrate in order to detect the impact response of silicon subject to drop weight impact loading. Figure 3 reveals the microfabrication procedures for making these microsensors. The low pressure chemical vapor deposition (LPCVD) method was used to deposit a 0.1µm thick silicon nitride (i.e., Si3N4) insulating layer as shown in Fig. 3(a). The insulating layer will only introduce 1 to 10 ns transmitting time due to the fact that the silicon nitride layer’s thickness is only 0.1µm, and this will introduce very limited effect to the dynamic strain measurement in the present application. Figure 3(b) shows that a 0.5µm thick polysilicon layer was subsequently deposited on top of insulating layer by the LPCVD method. This layer was then subjected to boron doping by an ion implantation machine and the ion concentration is set to be $3 \times 10^{19}$ cm$^{-3}$ as described in section 2 of this paper. Keep in mind that a 950°C annealing process must be taken in order to obtain a more uniform resistive property. After the boron-doped LPCVD polysilicon layer was produced the averaged measured sheet resistance could be calculated based on test data found by utilizing a four-point probe resistance measuring equipment.

Our micro strain gage pattern, as shown in Fig. 1, could not be obtained without a proper pattern transfer process. One to two µm thick S1818 positive photoresist was spin-coated on the top of the doped polysilicon layer. After the photoresist was cured, the UV lithography was applied to the specimen with a plastic photomask with our designed strain gage pattern on it. The exposure time was set to be 8 sec in the present application. Desired pattern can finally be obtained after proper chemical development and postbake, as shown in Fig. 3(c).

Figure 3(d) shows that the sensor pattern can be observed when the reaction ion etching (RIE) process was conducted. After we applied acetone to the surface of the wafer, the residual photoresist can be clear off, as shown in Fig. 3(e). At this stage, the silicon wafer was coated with an insulating layer and boron-doped LPCVD polysilicon strain gages are also mounted on top of the silicon nitride insulating layer.

Evaporation technique was furthermore used to deposit gold layer on the surface of the specimen. Notice that before producing the gold layer, a 0.02µm thick chromium interface layer needs to be deposited and this layer serves as the binder for gold layer and polysilicon. Figure 3(f) shows the lay out of specimen coated with a gold layer which was then patterned, etched, and cleaned in order to make the electric signal connection wires and terminals for microsensors as shown in Fig. 3(g).
Fig. 3 Descriptions for the microfabrication process for making the polysilicon strain gages on the top of silicon wafer

Photograph of thirty-two microfabricated polysilicon strain gages with gold connecting wires and terminals on a 4 in. circular silicon wafer. After the silicon wafer was carefully cut into pieces as shown in Fig. 4, the target bar with two micro strain gages mounted was obtained.

Again, the locations of these microsensors and the size of substrate target bar are presented in Fig. 2. The length and width of the target bar shown in Fig. 4 are 7.8cm (the clamped length of target bar is 0.9cm) and 0.375cm, respectively.

4. DROP TOWER IMPACT TESTS AND DYNAMIC SIMULATIONS

Before conducting the drop weight impact tests, we performed a series of calibration tests. Simple bending tests on the cantilever target bar with microsensor mounted were performed with various mass loaded to its free end. After we recorded the sensor’s detected signal, a plot of the voltage versus the computed bending stress at sensor location was plotted for ten different end mass loading conditions, as shown in Fig. 5. The apparent gage factor \( G' \) was determined to be approximately 14.1 for the present application. Notice that the theoretical gage factor for a piezoresistive sensor is defined as:

\[
G = 1 + 2\nu + \frac{\Delta \rho}{\rho_e} \epsilon.
\]

For both boron- and phosphorus-doped material the theoretical gage factor reported by Obermeier and Kopystynski (4) and French (8) was 25 to 40 for a doping concentration ranging from \( 10^{18} \) to \( 10^{20} \) cm\(^{-3} \). The difference seems to come from the microfabrication processes related to the doping process and annealing process, which may cause inhomogeneity and variation of the sensor properties. The relationship between the sensor measured signals \( V \), excitation \( V_e \) and the response strain \( \epsilon \) can be expressed as:

\[
\frac{V}{V_e} = G' \epsilon.
\]

In this study, the excitation voltage \( V_e \) was set to be 5 volt. This relationship will be used to convert the experimental detected voltage by sensor to the dynamic impact strain. A detailed description of the bridge type sensor signal condition circuit is referred to Ref. [15].

The rectangular silicon target bar with boron-doped polysilicon micro strain gages mounted on bar surface, as shown in Fig. 4, was then installed on a mini-type drop tower in order to conduct the drop weight impact test. The lower end of the target bar was clamped and the other end was free. A photograph of the setup of the present mini drop tower impact tester is presented in Fig. 6. Microsensors were connected to a bridge type amplifier for signal condition. After impact occurred, the sensor detected strain wave signal was recorded on a four channel Nicolet 460 digital oscilloscope. The impact velocity was detected by a pair of infrared velocity sensors. The 6mm diameter cylindrical steel impactor, weighing 3.3gm, is also shown in Fig. 6. This impactor was dropped from a prescribed height in order to strike the instrumented silicon target bar at an impact velocity of 2.5 and 1.7m/s. The mechanical properties of the steel impactor and the silicon target bar were tabulated in Table 1. The mechanical properties of the steel impactor and the silicon target bar were
Fig. 5 A plot of the voltage versus the computed bending stress at sensor location for a various end mass loaded

Fig. 6 Photographs of the drop tower impact tests

Table 1 The mechanical properties of impactor and target bar materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Impact rod</th>
<th>Target bar&lt;sup&gt;10&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>7,800</td>
<td>2,330</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>200</td>
<td>130</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
<td>0.28</td>
</tr>
<tr>
<td>Longitudinal elastic wave speed (m/s) under conditions of plane strain, $C_{L} = \sqrt{\frac{E}{\rho(1-\nu^{2})}}$</td>
<td>5308.2</td>
<td>7,780.8</td>
</tr>
<tr>
<td>Longitudinal elastic wave speed (m/s), $C_{L}$ = $\sqrt{E/\rho}$</td>
<td>5,063.7</td>
<td>7,469.5</td>
</tr>
</tbody>
</table>

The measured impact responses of these two gages were plotted in Fig. 7 for an impact velocity of 2.5m/s case. Table 2 shows eight test results containing the measured time difference of the elastic wave arrival time at these two micro strain gages, when specimens were impacted at the same initial velocity of 2.5m/s. Upon examining Table 2, it reveals that the averaged longitudinal elastic wave speed ($C_{L}$) and the averaged elastic modulus ($E$) of the target specimens obtained from impact tests are 7520.5m/s and 132GPa, respectively. The difference between these averaged values and the corresponding value given in Table 1 for the elastic wave speed and elastic modulus is within 0.7% and 1.5%, respectively. Note the mechanical properties for silicon target rod were obtained from Ref. [16]. In order to examine the elastic stress wave propagation in the target bar made of silicon with the prescribed micro strain sensors installed, an explicit transient finite element commercial code—LS-DYNA3D was adopted to analyze the current problem numerically. Figure 8 shows the finite element mesh models for impactor and target bar. The 800 steel impactor solid elements and 518 target shell elements (with a thickness of 500µm) were introduced to the present numerical model. Convergence tests have been performed in order to assure that the model element number used in simulations is able to result in an accurate numerical solution. Upon examining Figs. 7 and 9, the elastic wave arrival time difference of these two micro sensors is approximately 6.2µs from test data (observed from Fig. 7) and 5.9µs from the numerical simulated results (observed from Fig. 9). Based on the uniaxial elastic stress wave theory, an elapse time of 5.6µs is needed to propagate the elastic wave from one microsensor to the other one. Therefore, it is concluded that the deviation among (a) test results, (b) numerical solutions and (c) the unidirectional elastic stress wave theory predicted results of the elapse time for elastic wave to propagate between two microsensors is within 10.7% for the current study. Figure 9 also shows that the numerical simulated two stress waves, at these two microsensor locations, preserve a specific zig-zag pattern. The zig-zag pattern is due to the stress wave bouncing back and forth in the target bar after impact occurs. Similar patterns can also be observed in microsensor detected signals as shown in Fig. 7. Notice that the material constitutive model used in the current finite element analysis is the elastoplastic model, material damping is not considered in the
Table 2  A series of the measured time difference of the elastic arrival to these two gages when impact velocity is 2.5 m/s

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Measured time difference (Δt, μs)</th>
<th>Distance between sensors (μm)</th>
<th>Measured longitudinal wave speed, (m/s)</th>
<th>Error (%) compared with ( C_1 )</th>
<th>Error (%) compared with ( C'_L )</th>
<th>Calculated elastic modulus ( E ) (GPa)</th>
<th>Error (%)</th>
<th>Calculated elastic modulus ( E ) (GPa)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5</td>
<td>41850</td>
<td>7,609</td>
<td>−1.9</td>
<td>−2.2</td>
<td>134.9</td>
<td>3.8</td>
<td>124.3</td>
<td>−3.3</td>
</tr>
<tr>
<td>2</td>
<td>5.2</td>
<td>“</td>
<td>8,048</td>
<td>7.7</td>
<td>3.4</td>
<td>150.9</td>
<td>16.1</td>
<td>139.1</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>5.7</td>
<td>“</td>
<td>7,342</td>
<td>−1.7</td>
<td>−5.6</td>
<td>125.6</td>
<td>−3.4</td>
<td>115.8</td>
<td>−10.9</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>“</td>
<td>7,437</td>
<td>−0.4</td>
<td>−4.4</td>
<td>128.9</td>
<td>−0.8</td>
<td>118.8</td>
<td>−8.6</td>
</tr>
<tr>
<td>5</td>
<td>5.15</td>
<td>“</td>
<td>8,126</td>
<td>8.8</td>
<td>4.4</td>
<td>153.9</td>
<td>18.4</td>
<td>141.8</td>
<td>9.1</td>
</tr>
<tr>
<td>6</td>
<td>5.35</td>
<td>“</td>
<td>7,822</td>
<td>4.7</td>
<td>0.3</td>
<td>142.6</td>
<td>9.7</td>
<td>131.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>7,730.7</td>
<td></td>
<td></td>
<td>139.5</td>
<td></td>
<td>128.5</td>
<td></td>
</tr>
</tbody>
</table>

1. Compared with the longitudinal elastic wave speed \( (C_1) \) (i.e. 7,469.5 m/s) given in Table 1.
2. Compared with the longitudinal elastic wave speed with conditions of plane strain \( (C'_L) \) (i.e. 7,780.8 m/s) given in Table 1.
3. Using longitudinal elastic wave speed, \( i.e. \ C_1 = \sqrt{E/\rho} \), to calculate the elastic modulus.
4. Using longitudinal elastic wave speed with conditions of plane strain, \( i.e. \ C'_L = \sqrt{E/\rho(1-\nu^2)} \), to calculate the elastic modulus.

The application of polysilicon as the strain gage material is not new. However, a complete description of the microfabrication processes utilizing the facilities located in the Micro-nano research technology center, NCKU, Tainan and the Center for Nano-Science and Technology in the UST, Hsinchu is reported in this work. The gage factor of the microsensor fabricated using the present process was also calibrated. The current strain gage sensors’ manufacturing process is different from the available commercial strain gage sensors. Notice that (1) the gage length of the current microfabricated polysilicon strain gage is 0.85mm and which is smaller than most of the commercial metallic foil strain gage. If a glass optical mask is used, we can furthermore reduce the gage length; (2) Present micro strain gage was directly deposited on the surface of target with an 0.1μm thick

![Fig. 8 Numerical mesh model for the impactor and target bar](image)

![Fig. 9 A plot of the LS-DYNA3D finite element simulated strain gage response at these two micro strain sensors’ locations when impact speed is 2.5m/s](image)

The arrival of the 1st reflection wave to micro strain gage no. 1 and gage no. 2, respectively. Based on the uniaxial stress wave theory, the stress generated in two uniform bars of unequal cross-sectional area and dissimilar material when undergoing coaxial impact can be derived as

\[
\sigma_1 = \frac{\rho_1 c_1 V_1}{1 + 2A_1 \rho_1 c_1} \quad \text{and} \quad \sigma_2 = \frac{\rho_2 c_2 V_1}{1 + 2A_2 \rho_2 c_2}
\]

where subscript 1 and 2 stand for the impact bar and target bar, respectively. Variables \( \rho \), \( c \) and \( A \) are the density, elastic wave speed, impact velocity and cross-sectional area of the structure element in question. The impact velocity is denoted by \( V_1 \). Based on Eq. (4), the stress level (\( \sigma_2 \)) in the target bar after impact occurred can be calculated to be 42.3MPa. This unidirectional stress wave theory predicted stress level in the target bar is very close to the test value of 42MPa and finite element simulated value of 42.9MPa reported here. Similar results can also be observed for specimen impact at an incident velocity of 1.7m/s (15). Therefore, it is concluded that current boron-doped LPCVD polysilicon strain gage seems to be able to detect the elastic stress wave response in a mini-type structure.

numerical simulations. Therefore, the ringing phenomenon is quite clear in numerical solutions. Upon examining the peak stress wave amplitude of the target bar before the first reflection stress wave returns to micro strain gage no. 1 as shown in the Figs. 7 and 9, it reveals that a stress level of 42MPa and 42.9MPa can be found from test results and numerical solutions, respectively. Note that points A and B given in Fig. 9, correspond to
insulating silicon nitride layer in between. However, the commercial strain gage needs to be glued on the surface of target; (3) The current strain gage possesses higher gage factor and improved sensitivity than most of the commercial metal foil gage made of alloy; (4) The current strain gage manufacturing process is compatible with the semiconductor fabrication process, while the commercial strain gage is not.

5. CONCLUSIONS

The boron-doped polysilicon micro strain gages have been fabricated for a mini-impact system. The sensor’s gage factor has been calibrated. A rectangular silicon wafer structure with these micro strain gage mounted was used as the target bar struck by a small cylindrical steel rod traveling at an impact velocity of 1.7 and 2.5m/s. The elastic wave speed and elastic modulus of silicon are experimentally determined, and the deviation of these test values to that found by using the finite element program and the unidirectional stress wave solution are limited. It is reported that the averaged elastic wave speed ($C_1$) and the average elastic modulus ($E$) of the target specimens obtained from impact tests are 520.5m/s and 132GPa, respectively. The difference between these averaged value and the reference value (16) shown in Table 1 for the elastic wave speed and elastic modulus is within 0.7% and 1.5%, respectively. In addition, upon examining the wave response of the target bar before the first reflection stress wave returns to microsensors, it reveals that a stress level of 42MPa and 42.9MPa can be found from test results and numerical solutions, respectively. These values are very close to the unidirectional stress wave theory predicted stress level of 42MPa in the target bar. It is concluded that current boron-doped LPCVD polysilicon strain gage seems capable to detect the stress wave in a mini-structure.

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