Application note

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FTIR measurement of epitaxial film thickness applications

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Introduction

Many spectroscopic methods aid in the measurement of thin films significant to the fabrication of integrated circuits. Methods like ellipsometry, variable angle monochromatic observation (VAMFO), constant angle reflection interference spectroscopy (CARIS), and film absorption measurements have been documented. Infrared spectrometers are often used to determine epitaxial (Epi) layer film thickness because the most commonly used high-resistivity Epi layers are transparent to infrared radiation. In fact, the common structure of Epi wafers lends itself quite well to infrared observation, whereas with visible observation and ellipsometry, these measurements range from more complex to impossible.

Quick, accurate, and precise determination of the Epi layer thickness is necessary in wafer production. Deposition of the Epi layer is one of the first processing steps, so the sooner an undesirable result is detected, the more time and money is saved in generating new, acceptable material for subsequent fabrication steps. The thickness of the Epi layer is an important consideration for the isolation of highly conducting wells, which are diffused, implanted, or deposited. Thickness is also a critical parameter affecting etch times.

In batch reactors, or systems in which several wafers have Epi layers grown on their surfaces simultaneously, it is important to monitor the consistency of the film over the wafers in extreme positions within the reactor chamber. Even in single-wafer systems, the uniformity of the Epi layer thickness is quite important, as subsequent processing steps will require a flat, uniform layer thickness to provide consistent device yield across the entire wafer surface. This is especially critical as wafer sizes increase; the current move to 300 mm wafers puts a high demand on reactor performance and the resulting film uniformity to ensure reasonable yields. To justify the investment in the equipment necessary to process 300 mm wafers, yields must be maintained or exceed the levels for smaller diameter processes.

Three major types of structures have been measured for Epi film thickness. Older design discrete devices make use of relatively thick Epi layers for the fabrication of bipolar transistors. The Epi layer serves as a collector in this structure, and is usually p material on a p+ substrate or n material on an n+ substrate. In bipolar integrated circuit (IC) structures, often an n-type material is grown over a p-type substrate. Ion implant of diffusion is used to produce wells of highly doped n+ material, which produces effectively an n-on-n+ structure in a limited geometric area on the wafer. More recently, lightly doped, thinner Epi layers have been applied in the growth of CMOS structures.

These Epi layers serve to isolate current carrying features, which reduces substrate noise, cross-talking, and latch-up. This is particularly significant as feature size is reduced.

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The infrared measurements of Epi layer thickness are usually accomplished by three different methods. All three methods are constant-angle observations making use of either direct or modified measurement of interference phenomena. This application note describes the three methods of interpretation, the relationship between them, and the advantages of each approach.

Infrared analysis of epitaxial film thickness

For Epi layer thickness measurements, the main benefit of the Fourier transform infrared (FTIR) technique is the speed of the measurement. Other benefits are that the FTIR thickness measurement is non-destructive and reproducible, lends itself to automation, and is operator independent.

Raw data from an FTIR spectrometer generally take the form of an interferogram, which can be described as a summation of cosine waves. A detailed explanation for this can be found in the Thermo Fisher Scientific publication “Introduction to FTIR.” The tool configuration used for the measurement of Epi film thickness is reflectance, where an incident beam of light is observed after it has hit the surface of the wafer. A schematic of this arrangement is presented in Figure 1.

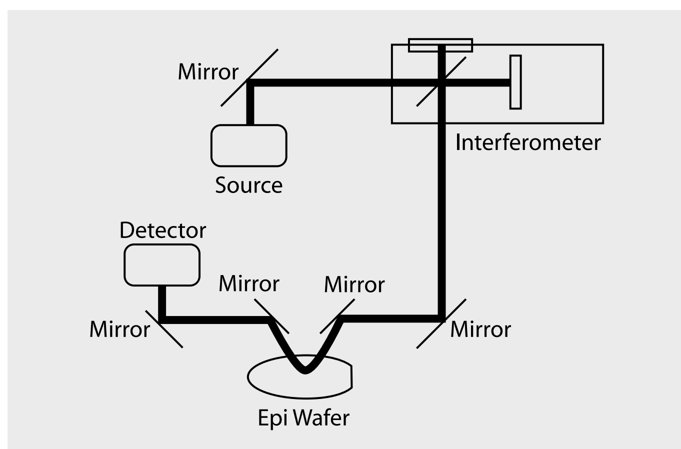

Figure 1: Optical schematic of the FTIR spectrometer module and the reflectance position used for the sampling of Epi wafers. Radiation from the IR source is modulated in the interferometer, reflects off the surface of the Epi sample and creates the signals later analyzed for thickness values.

A close examination of the surface of the Epi wafer illustrates the principle of the measurement. Infrared radiation penetrates and transmits through the lightly doped Epi layer reflecting off the interface between the Epi layer and the heavily doped substrate. As the doping of silicon increases, or as the resistivity decreases, the silicon becomes more metallic and more opaque to infrared radiation. The difference in resistivity (doping) between the Epi layer and the substrate, along with the sharpness of the interface, determines the strength of the thickness measurement signal. Such effects as diffusion or autodoping, which tend to blur the interface in depth, will reduce the thickness measurement signal. Figure 2 presents a diagram of the reflected radiation and an idealized Epi wafer (not shown to scale).

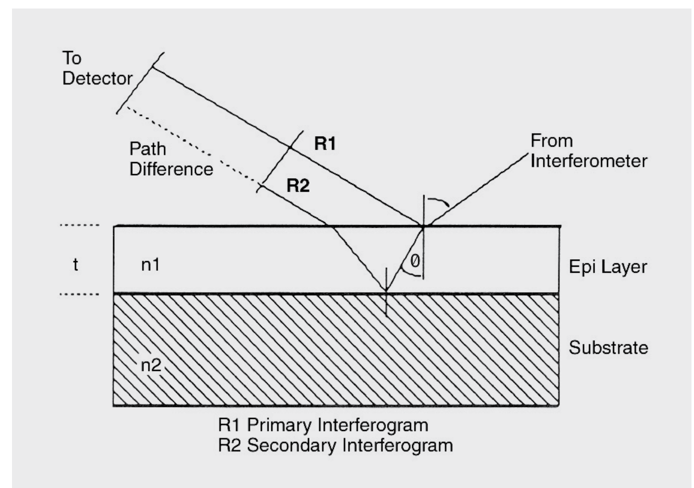

Figure 2: Epi wafer reflection radiation exiting from the interferometer impinges the surface of the Epi layer. A large portion reflects from the surface and forms the primary reflection o, in the case of the interferometer, the primary interferogram. The remaining radiation penetrates the Epi layer and reflects from the interface of the Epi and substrate, giving rise to the secondary reflection or secondary interferogram. The retardation or path difference between the two reflections produces an interference pattern, which can be processed in several ways to relate to the thickness of the Epi layer. The path difference between the two rays R1 and R2 is specifically a function of the index of refraction (or doping level) of the Epi, the cosine of the angle, and the thickness of the Epi layer, t. Observation of the path difference with the known Epi type allows a direct solution of the thickness (t).

Figure 3 shows a common structure encountered in bipolar devices or ICs. A reference material is typically run, not as a calibration standard, but to null all signals that are not a result of the difference in pathlength between R1 and R2. Typically, the intensity of the secondary interferogram R2 is much less than that of R1. The reference material allows nulling of a major portion of the R1 signal by use of subtraction. The purpose of the reference is to null the reflectance signal format of the top surface of the Epi film, so the best reference is often another Epi film with a markedly different thickness than that of the film of interest.

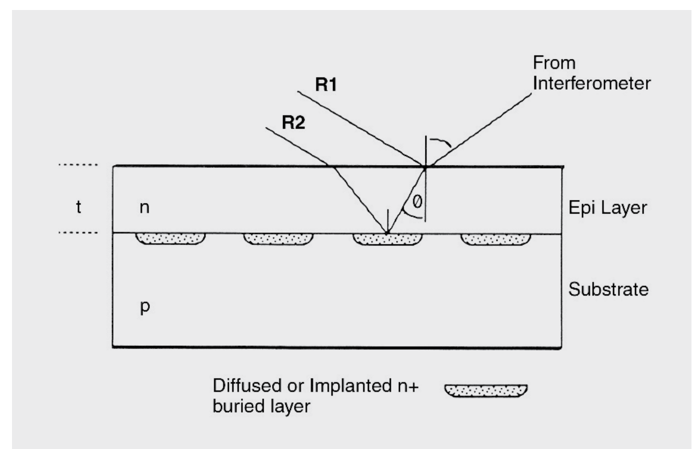

Figure 3: Buried layer structure. For the IR analysis of Epi layer thickness to work, the structure must be a higher resistivity layer deposited on top of a lower resistivity layer. Reflection takes place at the interface between the two, where the dopant level (and optical index of refraction) changes at the highest rate. In this structure, where an n Epi layer is deposited on a p substrate to form the collector for an NPN transistor, the n+ buried layer serves as the optical interface for the measurement. The resulting n-on-n+ measurement lends itself quite well to IR analysis. Typically, this type of structure would show a smaller or no R2 response in the absence of the diffused layer.

The choice of a proper reference is critical to the success of many interferometric Epi measurements. A proper reference should have Epi film and substrate doping identical to those of the samples of interest; if the structure has buried layers, the reference should have buried layers. The only difference should be the thickness of the Epi film. In general, the reference thickness should be outside the window of analysis for the samples. For example, if an Epi layer with a target thickness of 10 microns and an analysis range of 8–12 microns were being analyzed, a suitable reference would be less than 8 or greater than 12 microns in thickness.

Some structures can be measured without the use of a reference, but the accuracy of the result will suffer. In cases where the Epi/substrate interface is sharp and the difference in resistivity is large (ASTM specifies substrates < 0.02 ohm-cm with Epi > 0.1 ohm-cm), references will be less critical. If no reference is used, a clean front surface mirror must still be run as a means to gather a signal from the primary interferogram (R1) for later processing (or nulling). The front surface mirror has different reflectance characteristics than those of the surface of the Epi wafer; therefore, Thermo Fisher Scientific always recommends using a reference wafer for the highest accuracy and sensitivity.

All three methods of thickness determination make use of the path difference between rays R1 and R2, but the algorithms applied to determine thickness are different. Specifically, the three methods take place in different domains. Generally, a Fourier transform instrument is applied to the data set to examine it in a different domain.

Interferogram subtraction

The most straightforward measurement of the epitaxial layer thickness observes the distance between the location of the primary interferogram and the secondary interferograms, or sidebursts. This method utilizes the raw data or time domain. This technique typically relies on the subtraction of the signal from a reference material, which enhances the ability to observe the secondary interferograms. The material subtracted is often an Epi layer of a different thickness. Figure 4 shows the method of subtraction. As thickness (t) increases, the distance between the primary and secondary interferograms increases. An alternate approach to this measurement is to use the distance between the two secondary interferograms. This distance, divided in half, can sometimes give more reliable results than the measurement of a single side position relative to the centerburst.

The method of interferogram subtraction is the fastest measurement of Epi film thickness available because few calculations are performed on the signal. However, this technique does have its disadvantages:

1. When the Epi layer becomes thin (<2 microns), the secondary interferogram is difficult to discern because of its proximity to the primary interferogram, even after subtraction of a reference interferogram.
2. The signal-to-noise degrades, and precision can suffer.
3. There is no correction for phase error.

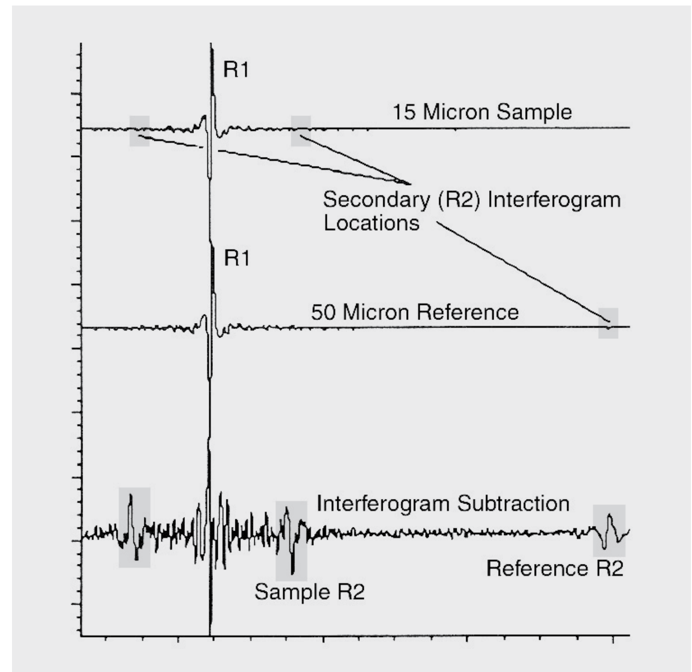

Figure 4: The interferogram subtraction method of Epi thickness determination. In this example, a 15-micron sample, shown above, is of interest. A 50-micron reference, the middle interferogram trace, is subtracted. Subtraction greatly enhances the ability to discern the secondary peaks in the interferogram. In this case, the secondary peak cannot be seen in the sample before subtraction. The distance between the centerburst R1 (the large feature in the sample and reference) and the secondary R2 determines thickness. As thicker Epi films are examined, this distance increases.

As a result, there can be confusion about selecting the proper part of the secondary interferogram for distance measurement. Several methods have been devised to correct for this problem, but none are totally successful as a general method.

Constant angle reflection interference spectroscopy

A second method of thickness determination comes from observing the interference maxima and minima in the spectral domain. The interference pattern results from different wavelengths of light being either reinforced or canceled as a result of the path difference introduced on the reflected radiation by the Epi layer. This technique has been called constant angle reflection interference spectroscopy (CARIS). It is used quite extensively in the visible region of the electromagnetic spectrum to measure the thickness of photoresist and dielectrics applied to wafers at various processing steps. However, the commonly used visible instruments cannot be used for Epi thickness analysis due to the opacity of silicon in the visible region of the spectrum.

The technique measures three variables:

1. The spacing between the extrema.
2. A minor correction for phase changes at the interface based on the resistivity of the substrate.
3. Calculations of thickness based on the observed spacing, the angle of incidence and the dopant level of the Epi layer.

This method is the basis for ASTM procedure F95–89. There are two major advantages to this method: it relies on the interpretation of data routinely presented by most commercial spectrometers, and theoretical curves can be generated and then compared with actual observed data.

The disadvantages of this approach are:

1. Error magnitudes are larger with decreasing thickness. At one micron, it becomes quite difficult to apply this approach due to the absence of a complete cycle for observation. In spectra of multiple layers, it is also much more difficult to determine extrema.
2. Noise in certain portions of the spectrum can give rise to errors in peak maximum locations. This is particularly a problem in thin layers having maxima in the areas of the spectrum affected by purge variations.
3. The usual approach is to consider only one or two cycles, so less averaging of the data typically takes place, resulting in lower precision.

Figure 5 presents the interference pattern obtained from three different thickness Epi films.

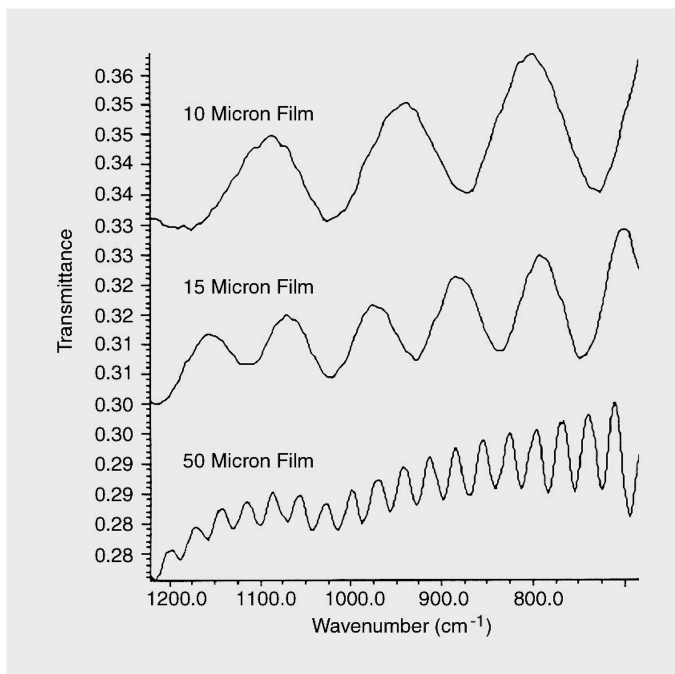

Figure 5: Interference extrema. The repeating pattern of constructive and destructive interference between the R1 and R2 rays gives rise to a series of minima and maxima. The spacing between these extrema is a direct measure of film thickness. As the Epi layer becomes thinner, the cycles become larger.

Despite all these considerations, this method has been quite successfully utilized for many structures. Due to its less demanding computational requirements, it has lent itself quite well to older infrared instruments without a computer interface.

Cepstrum

A third method, the Cepstrum, takes the difference of two spectral response curves (similar to the types of curves presented in Figure 5) and performs a second Fourier transform to yield data that is displayed as intensity versus thickness. After phase correction, this data often show a peak corresponding to the film depth where the maximum change takes place in dopant concentration. This method has several advantages:

1. It uses phase correction after data collection, resulting in a more symmetric peak shape for subsequent thickness analysis.
2. It makes use of the entire spectral data domain.
3. It compensates well for the reference and often enhances the size of the thickness peak relative to the background signals.
4. It has more sensitivity for fractional-area buried layers, as well as smaller differences in resistivity between the Epi layer and the substrate. For complex Epi layer structures or multilayer structures, it often allows observation of the multiple peaks. This is the recommended approach to this analysis because it has the best precision and accuracy. For submicron analysis, it is the only reliable method.

Figure 6 presents the flow of calculations involved in an analysis. It should be noted that the Thermo Scientific™ Cepstrum analysis is a **direct** measure of thickness from the data acquired from the sample. Other approaches, including “curve-fitting,” are **estimates** based on the “fit” of the theoretical curve to the sample data and can introduce errors in the determination, which becomes significant at thinner dimensions (Figure 7). Typical Cepstrum precision in submicron analyses has been shown to be at 0.002 micron levels and below, and accuracy is in agreement with SEM cross-section determinations of the thickness at the locations probed by the infrared tool.

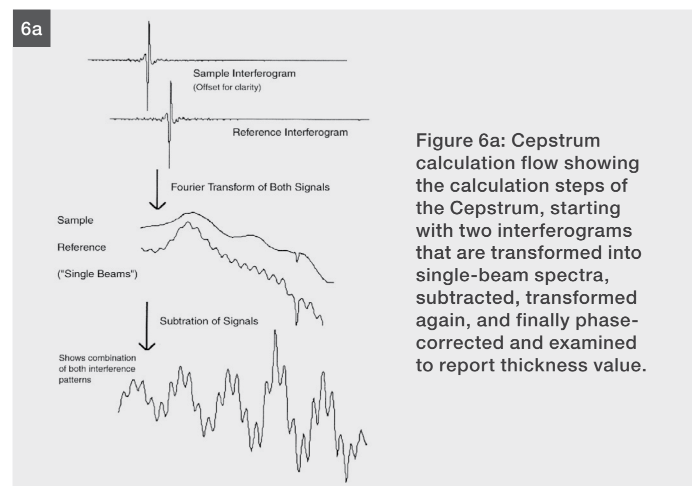

Figure 6a: Cepstrum calculation flow showing the calculation steps of the Cepstrum, starting with two interferograms that are transformed into single-beam spectra, subtracted, transformed again, and finally phase-corrected and examined to report thickness value.

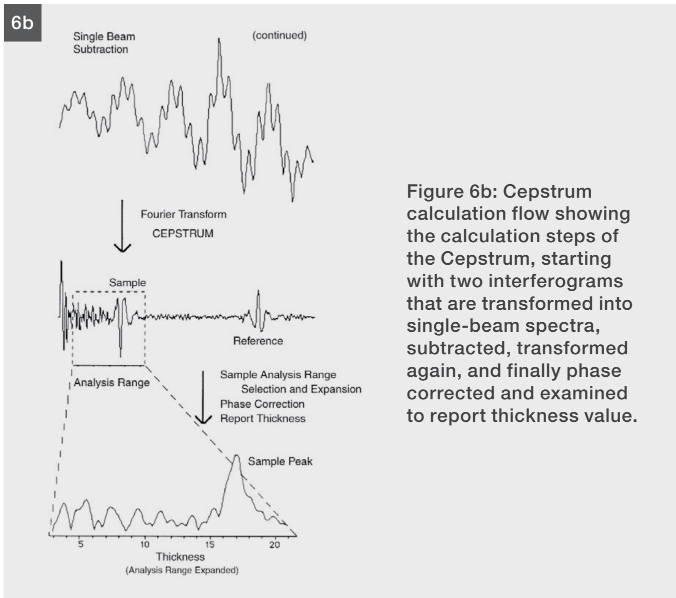

Figure 6b: Cepstrum calculation flow showing the calculation steps of the Cepstrum, starting with two interferograms that are transformed into single-beam spectra, subtracted, transformed again, and finally phase corrected and examined to report thickness value.

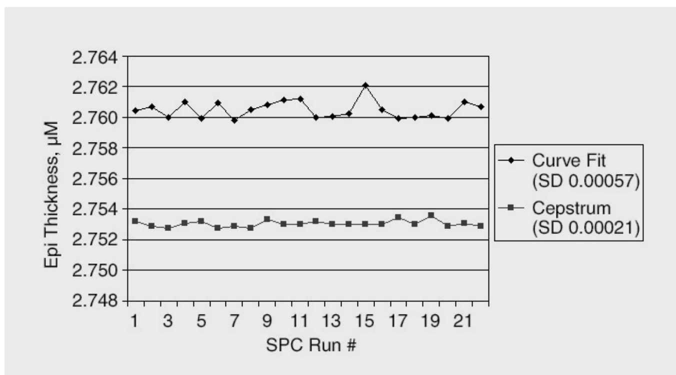

Figure 7: Comparison of the precision of a Thermo Scientific Cepstrum algorithm and a curve-fitting based algorithm.

Finally, Figure 8 shows a comparison between the raw sample data interferogram, the interferogram subtraction result, and the Cepstrum for a 3-micron Epi layer sample and a 16-micron reference. The selection peak maximum is more straightforward in the Cepstrum waveform as a result of the phase correction used in the Fourier transform technique.

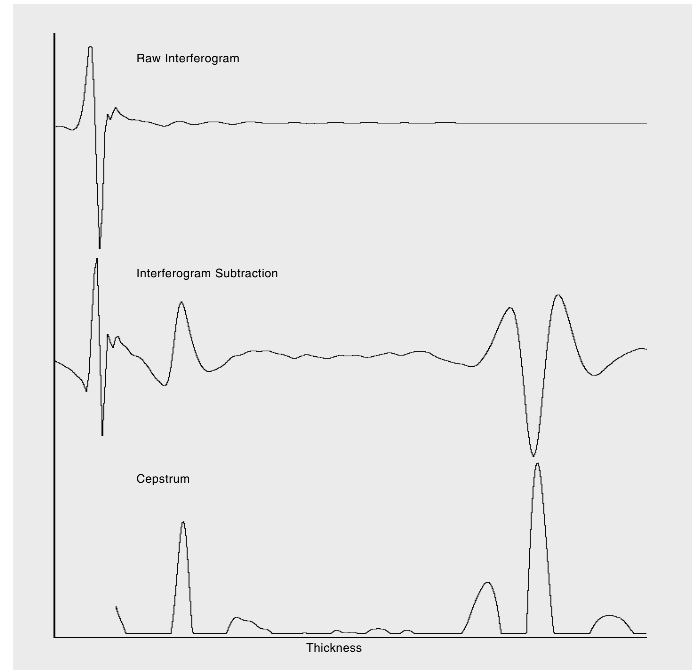

Figure 8: Data comparison. The raw interferogram from a 3-micron sample is shown above, along with the result of an interferogram subtraction and a Cepstrum calculation using a 16-micron reference. The peak shape generated by the Cepstrum is easier to interpret: the distance from the secondary reflection maximum relative to the position of the primary reflection is more obvious, and not as likely to suffer from confusion between the positive and negative lobes (the central maximum is selected). Note that in the raw data, the secondary burst is not discernable.

Conclusion

FTIR provides a fast, precise method of measuring the epitaxial layer thickness encountered in many of today's IC structures. As the industry demands the use of thinner Epi layer structures for new IC designs, different infrared methods may be required to perform the measurements. The practical limit for Cepstrum calculations has so far been shown to be 0.25 microns. Such difficult samples as a 10 W-cm Epi layer on 1 W-cm substrates have been measured, as well as samples with less than an order-of-magnitude difference in dopant levels.

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