Abstract—We present a new method for in-situ measurement of substrate camber, the deformation introduced by the epitaxial layer being grown on the substrate. Similar to the currently employed laser beam deflection method, we measure the radius of curvature from the inclination angle $\alpha(z)$ of the wafer surface, during the wafer rotation under the observation window of an MOCVD chamber. But, instead of the commonly used triangulation, based on a laser plus a position-sensitive detector, we employ a non-contact self-mixing interferometric detector, based on a diode laser projecting a spot onto the wafer surface and detecting the backreflection with the laser itself. Advantage of the new method is that separation of source and detector is eliminated and the substrate and film thickness, respectively.

The inclination angle $\alpha(z)$ can be measured with the new method as

$$S \approx \frac{E}{(1-\nu)} \left( \frac{t_{sub}^2}{t_f} \right) \frac{\eta}{R}$$

where $E$ is the substrate Young's modulus, and $t_{sub}$ and $t_f$ are the substrate and film thickness, respectively, and $\nu$ is a factor of the order of unity describing the shape of the substrate (e.g. $\nu \approx 0.166$ for a long thin slab with $l_x > l_y > 5l_z$).

Several methods have been proposed for measuring the curvature radius, including interferometric and wavefront analyses, ultrasound and X-ray diffraction (see [3] for a review), but the most commonly employed is the so called laser beam deflection (LBD) [4]. Here, the laser beam is collimated and projected on the surface of the substrate, and the reflection is observed using a position sensitive detector (PSD), resolving minute deviations of the spot away from the undeflected position of the plane surface reflection.

With a 1-mW HeNe laser and a linear 5-mm PSD, Scarminio et al. [5] were the first to resolve deflections of $\Delta \alpha = 10$ $\mu$rad on a 3-mm×30-mm stripe-shaped substrate, with a maximum measurable deflection up to 2 mrad; the corresponding curvature radius was from 3 km to 15 m, and the internal stress for the materials used were estimated to range from 0.2 to 10.6 $10^3$ Nm$^{-2}$.

To achieve the desired $\Delta \alpha$, however, a long baseline $d=450$ mm between wafer and PSD was necessary (to get a large $d \times \Delta \alpha$ deviation on the PSD), the go-and-return path required a beamsplitter, and the integration time was relatively long, about 1 s.

Later, Floro and Chason [6] introduced a variant of the beam deflection method, consisting in the use of a multi-beam etalon splitter and a CCD sensor in place of the PSD to simultaneously carry out the measurement on several points of the substrate surface, thus improving immunity to ambient-induced vibrations and reducing the integration time.

In all LBD approaches, the minimum $\Delta \alpha$ (and the maximum R, in view of the constitutive equation $\alpha \propto \eta D/2R$ [4], $D$ being the wafer diameter) is set by the ratio $w_0/d$ of beam spot to baseline distance, multiplied by the fraction $\eta$ of beam size that can be just resolved by the PSD. To achieve 10 $\mu$rad with a $w_0=5$ mm and $\eta=10^{-3}$, a long $d=0.5$-m baseline is normally required.

In this paper, we propose a self-mixing detector [7,8] as the sensor of the deflection angle generated by the reflection on the surface under test. The self-mixing detector has an excellent capability of resolving very small angles down to 0.5 $\mu$rad [9], with a short response time (about ms), and incorporates its own photodiode (the power monitor photodiode already available in the laser diode package) for the conversion into an electrical output.

Additionally, it doesn't require any beamsplitter or other optical component external to the laser, and can measure local radius distributions with the resolution of the spot size.
w_{0} \ (\text{typ.}<1 \ \text{mm}) \text{ using a small window (typ. 5-mm diameter) for access to the epitaxial-growth chamber.}

II. LAYOUT OF THE MEASUREMENT

Consider a wafer for epitaxial layer presenting a top surface to the measuring station, like in Fig.1. The quantities related to the surface curvature are: the profile height z(x), where x is the axis of wafer translation, the inclination angle \(\alpha(x)\) of the surface tangent, and the radius of curvature \(R(x)\).

![Diagram](image)

Fig.1 Quantities related to the wafer curvature: \(z(x)\) is the local height, \(\alpha\) the inclination angle, and \(R\) the radius of curvature. The wafer is moved along the \(x\)-axis by the wafer carrier rotation. The measuring SMI is placed at height \(H\) and collects the returning beam, deflected of \(2\alpha\).

From differential geometry, the relations between the three quantities are written as:

\[
dz(x)/dx = \tan \alpha(x) \approx \alpha(x) \quad \text{(for small } \alpha) \quad (1a)
\]

\[
d^2z(x)/dx^2 = d\alpha(x)/dx = 1/R \quad (1b)
\]

We can measure \(R\) either: (i) by measuring the inclination angle \(\alpha\) with an angle sensor looking at the deflection angle \(2\alpha\) developed by the reflection at the wafer surface (Fig.1) and then computing the first derivative \(d\alpha/dx\) as indicated by Eq.1b, or (ii) by measuring with an interferometer the optical pathlength \(\phi=2kz(x)\), where \(k=2\pi/\lambda_{o}\) developed as the wafer is moved along \(x\), and then calculating the second derivative \(d^2z(x)/dx^2\) (Eq.1b).

Both methods can be implemented by a self-mixing configuration of interferometry (SMI, see [7] for a recent review), based on the modulation induced by the optical field backreflected by the surface into the laser cavity. Of the returning field, we will look at either the variations of optical pathlength \(\phi\), or to the tilt-induced dependence on \(2\alpha\) of the amplitude re-entering the laser cavity.

Optical pathlength variation is read by the SMI as a power signal \(P=P_{0} [1+mF(\phi)]\), where \(P_{0}\) is the quiescent power, \(m\) is an index of modulation and \(F(\cdot)\) is a periodic function of the argument, mod \(2\pi\), with a shape depending on the strength of feedback, but being a cosine function at weak feedback, as in a normal interferometer [7].

Angle \(2\alpha\) is measured from the dependence \(P=P_{0}(2\alpha)\) of the quiescent power \(P_{0}\) on the power returned into the laser cavity after reflection at the wafer surface. This quantity is given by the superposition integral of field distributions leaving and returning to the laser output mirror.

So, in general we may write the complete SMI signal as

\[
P = P_{0}(2\alpha) [1+mF(\phi)]
\]

(2)

An analysis of the ultimate sensitivity (based on the arguments developed in [10]) shows that performances of the two methods are nearly equivalent.

On the other hand, in the practical implementation there are significant differences. The angle measurement requires no extra optical component and the small phase signal \(mF(\phi)\) is easily filtered out from the dc dependence \(P_{0}(2\alpha)\). Instead, in the optical phase measurement we shall avoid the \(2\alpha\)-beam deflection causing a large variation [the \(P_{0}(2\alpha)\) term] superposed to the small interferometric signal \(mF(\phi)\). To do so, we can introduce a spherical mirror, with the center of curvature coincident with the laser spot on the wafer, so that the reflected light traces back the path and returns exactly into the laser. This ensures that \(P_{0}(2\alpha)=\text{const.}\), but requires a rather bulky and critical-to-align mount.

So we prefer an angle measurement for the simpler setup and the larger signal available, easily processed to find \(R\). We can either measure the radius dependence on \(x\) as \(1/R(x)=d\alpha(x)/dx\), or just the average \(R\) calculated as \(1/<R>=[(\alpha(0)-\alpha(D))/D\), where \(D\) is the wafer diameter and \(\alpha(0), \alpha(D)\) the angles at the edges \((x=0 \text{ and } x=D)\) of the wafer.

III. THE SELF-MIX ANGLE MEASUREMENT

We use an objective lens to focus the outgoing laser beam of spot size \(w_{0}\) onto the wafer placed at distance \(H\). After the deflection \(2\alpha\) imparted by the wafer (Fig.1), the beam returns back to the lens with the same spot size \(w_{0}\) but a lateral displacement \(2\alpha H\). By calculating the superposition integral of the two offset spots, outgoing and returning Gaussian-mode distributions, we find the resulting power as:

\[
P_{d}(\alpha) = P_{0} \exp \left( -\frac{(2\alpha H)^2}{w_{0}^2} \right)
\]

(3)

The trend of Eq.3 is fairly well matched (see below) by the response of the experimental setup, which is simply made up of a laser diode with internal monitor photodiode and a collimating objective lens. To have an almost circular spot, we choose a VCSEL laser, model PH85-F1P1S2-KC of Optowell Co., emitting 8 mW at 850 nm with a nominal drive current of 20 mA.

First, the P-I characteristics were measured with several test reflective surfaces representative of the wafer (sapphire, Silicon and Ni-plated Si). The results are reported in Fig.2 and show that, at the increase of the reflectivity \(r_{l}\) of the target, the emitted power \(P_{0}\) increases markedly, of about 1.8% for every % of reflectivity increase. Also the laser threshold current \(I_{th}\) is affected by feedback, and decreases
as reflectivity $r_3$ increases. The experimentally observed changes of power slope $dP/dI$ and threshold $I_{th}$ are consistent with those predicted by the Lang Kobayashi equations [7,11] with the normally assumed values of parameters.

To test the response of the system, we can either move the line of sight to the target (Fig.1) by mounting the laser on a piezo actuator as already introduced in [12,13], or tilt the substrate by a suitable mechanical actuator.

To demonstrate the measurement principle, we choose a loudspeaker as actuator, mounting the wafer on a side of it and spotting the pivotal point of the wafer surface to get a sizeable angle $\alpha$ and a negligible displacement $s$.

The results are reported in Fig.3. As we can see, the response is about Gaussian in shape, with a full-width at half maximum of 7 mrad. Now, as it is well known [8,9], by differentiation we can readily transform the response into a quasi-linear one. To do so, we apply a small modulating signal to angle $2\alpha$, and analyze the fundamental component of the SMI signal by a lock-in amplifier. In this way (inset a, b, c of Fig.3), we get a quasi-linear response (bottom left).

The angle modulation displayed in Fig.3 (inset at right) is about 0.5 mrad in amplitude, and the waveform is very clean. The noise is about 5 $\mu$rad, and using $<R>-D/A2\alpha$ it corresponds to a maximum measurable radius $R_{\text{max}}=50\text{mm}/5\mu\text{rad}=10\text{ km}$ in the present setup. However, the quantum noise limit is much smaller, down to about 0.05 $\mu$rad [8,9], and thus, potentially, radii up to 1000 km are in the reach of the SMI measurement.

Finally, the dynamic range is limited by the response curve width to a maximum angle of about 3.5 mrad, that is, a minimum measurable radius of $R_{\text{min}}=D/A2\alpha=16\text{ m}$.

Acknowledgements. Work sponsored by National Science Council of the Republic of China, Taiwan, contract NSC 103-2218-E-005-004. Authors thank Shun-Ji Shih and Ming-Chih Lee for the skillful help in laboratory activity.

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