HECTOR: trans-nanometer Z-axis calibration artifacts for semiconductor process control

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ABSTRACT

An electromagnetic Lorenz force transducer has been coupled to an Angstrom^{tm} elastic transducer to form a new compound transducer in which the displacement output is proportional to the current input. It is called the HECTOR^{tm} transducer and has been built in a form which provides very small displacements (in the range of nanometers) in response to modest currents (tens of milliamperes). The transduction effect is shown to be linear and hysteresis-free which provides for accurate calibration of the transducer and highly repeatable performance.

The HECTOR transducer can generate reliable and repeatable small displacements in the trans-nanometer region: that is the region characterized by dimensional sizes between about 100 nm. and smaller than an angstrom. HECTOR's displacements may be used as physical artifacts in the calibration of metrology instruments. This paper describes HECTOR's operating principles and calibration techniques and discusses the accuracy and stability of the artifacts that HECTOR can generate.

Key words: Ångstrom, nanometer, calibration, artifact, HECTOR

1. INTRODUCTION TO HECTOR'S OPERATING PRINCIPLES

HECTOR is a compound transducer composed of an electromagnetic Lorenz force transducer which drives an elastic Ångstrom transducer to produce a displacement that is proportional to the current input to the coil of the Lorenz force device. A Lorenz force transducer is composed of a magnetic field generated by two permanent magnets and a coil of wire which can carry a current in the magnetic field. Lorenz's law stipulates that the current will generate a reaction force that is proportional to the magnetic field (B), the current (i) and the length (l) of the current carrying wire in the field,

$$F=iBl. \qquad (1)$$

Ångstrom elastic transducers have been shown to be linear and hysteresis free to one part in ten thousand (1:10,000). They are described fully elsewhere (Hatheway, 1989, 1994, 1995, 1996) and are characterized by their effectiveness ratio (E. R.), the ratio of the output motion (Xo) to the input motion (Xi),

$$Xo=(E.\ R.)Xi \qquad (2)$$

The design of the elastic transducer is covered by U. S. Patent No. 5,187,876.

In HECTOR the force of the Lorenz force transducer (F) is coupled to the input displacement of the elastic transducer by the stiffness of the elastic transducer's structure. According to Hooke's law this is a linear relationship,

$$F=kXi. \qquad (3)$$

HECTOR's behavior is then governed by the simultaneous application of these three physical laws which combine to form the law which controls the behavior of the compound transducer,

$$Xo=(E.\ R.)(Bl/k)i \qquad (4)$$

which shows HECTOR's output displacement (Xo) to be proportional to the input current (i) when the effectiveness ratio, the magnetic field, the coil geometry and the stiffness are constant. The transduction effect is,

$$Xo/i = (E.\ R.)(Bl/k). \qquad (5)$$

The configuration of the HECTOR transducer is shown in Figure 1. The Lorenz transducer's permanent magnets are attached to the top of the elastic transducer and its coil is attached to the base of the elastic transducer. Current (i) in the coil will produce bending moments in the structure of the transducer which will move the silicon target up and down (Xo). The elastic transducers provides three spherical feet in its bottom surface which provide kinematic support for the transducer on a flat surface and also allow the elastic structure to deform freely under the influence of only the force (F) from the Lorenz force transducer. A BNC electrical connector provides for connection to an external source of the current. A switch selects among HECTOR's five operating channels.

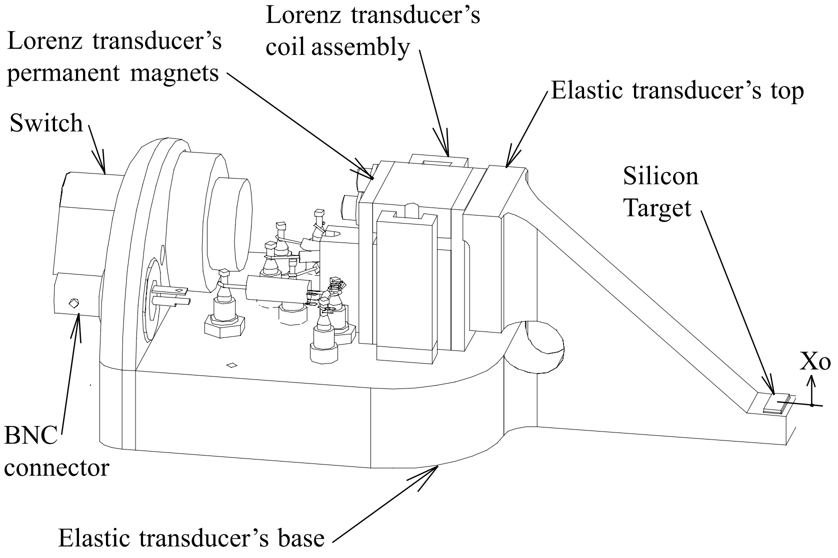

Figure 1. HECTOR's configuration.

The behavior of the transducer has been studied to verify the applicability of equation (4). Figure 2 shows a typical "hysteresis loop" from the study. It applied currents up to about .15 amperes and measured the displacement response of HECTOR at the target using capacitance gages. The results are completely linear with no perceptible hysteresis. The only deviations from complete linearity are from noise which creates uncertainties in the measurements on the order of .03 to .05 nanometers.

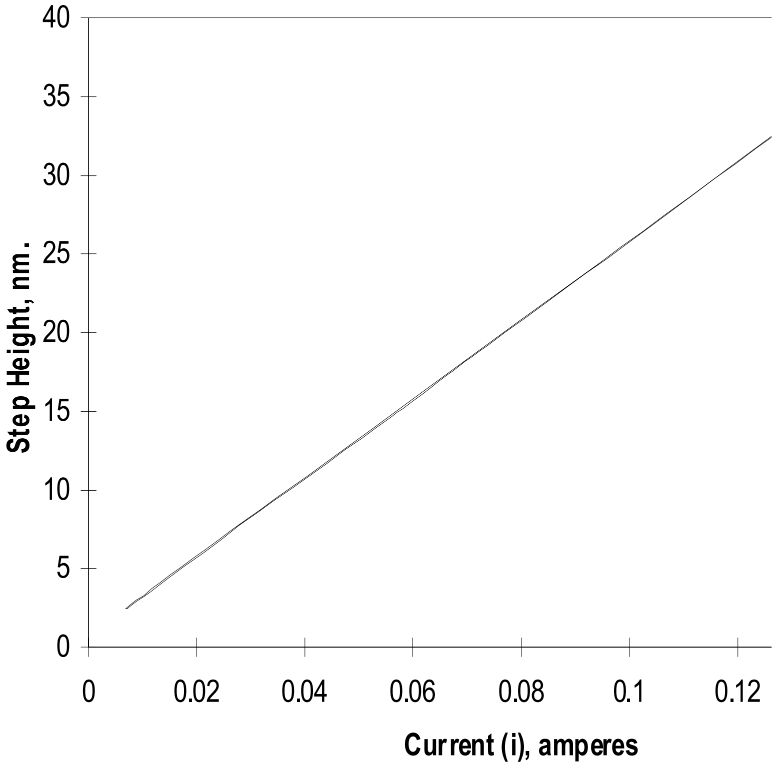

Figure 2. HECTOR's hysteresis looop.

HECTOR offers five operating channels which are selected with a five position rotary switch. The channels are labeled at the switch "100.," "10.," "1.," ".1" and "User." The first four channels with (numerical labels) generate fixed size artifacts. The nominal size of the artifact corresponds, in nanometers, to the numerical label of the channel, i.e.., the channel labeled “1.” produces a 1. nanometer size artifact. These four channels are designed to be used only in conjunction with the HECTOR controller which is provided with the HECTOR transducer. The controller contains batteries, the current from which is regulated by electronic circuits in the HECTOR transducer. The controller is operated by a switch. A pilot light indicates the condition of the charge in the batteries. These four channels operate HECTOR in the Fixed Mode. The Fixed Mode is intended to provide the user an easy way to generate a few fixed size artifacts which are repeatable and simple.

The fifth channel, labeled “User,” is provided to generate artifacts of any size up to one micrometer. An operator may do so by selecting the User channel at HECTOR’s switch and providing his own current source which he connects to HECTOR at the BNC connector. With the User channel selected the current supplied at the BNC connector is routed directly to the coil of the Lorenz force transducer. A typical user’s current source may be a regulated current laboratory power supply, a calibrated ammeter and a switch. With such a setup an operator may adjust a supply to the desired current which he measures to a desired accuracy with the ammeter. By supplying the current to the BNC connector on HECTOR the user “creates” his own artifact with HECTOR of a size determined by the magnitude of the current. The size of the User artifact is determined by the magnitude of the current supplied by the user’s current source. The repeatability of the User artifact is controlled by the stability of the user’s current source. The accuracy of the User artifact is affected by both the accuracy of HECTOR’s calibration and the accuracy of the user’s ammeter. This is called the User Mode of operation of the HECTOR artifact.

HECTOR provides the operator two modes of operation: the Fixed Mode provides the operator four easily generated fixed-size artifacts from .1 nanometers to 100 nanometers; the User Mode permits the operator to generate artifacts of any size under about one micrometer. The accuracy of the two modes is likewise different: the accuracy and repeatability of the artifacts in the Fixed Mode are limited to about three decimal places by the simple electronic circuits incorporated in the transducer; the accuracy and repeatability of artifacts in the User Mode are unlimited and depend only upon the quality (accuracy) of HECTOR’s calibration, the quality of the operator’s controlling electronics and, in very precise work, on the stability of the local environment. The hysteresis loop shown in Figure 2 was prepared in User Mode.

2. HECTOR’S CALIBRATION

HECTOR’s calibration involves the independent calibration of one or more channels of the HECTOR transducer. The four fixed-size channels are operated through the HECTOR controller during their calibration and the calibration data is the absolute size of the four artifacts produced by the four channels, usually measured in nanometers. Depending upon the calibration procedure the data may include statistical measures of inaccuracy or uncertainty in the sizes as well.

The User channel is operated from the user’s electrical current supply during calibration and the calibration data will be the channel’s transduction effect, usually measured in nanometers per ampere. As with the fixed-size channels, the User channel calibration may include statistical measures of inaccuracy or uncertainty.

Calibration of any of the channels requires the measurement of the displacement of the silicon target. The displacement may be measured by either a contact stylus instrument or an interferometer. Since the silicon target reflects visible light the displacement measurements may be made traceable to the SI unit of length, the wave length of light, by using an interferometer with a light source of stable wave length.

Two of HECTOR’s channels were calibrated at the National Institute of Standards and Technology (NIST) using the instruments and methods for calibrating conventional step-height artifacts. Their instrumentation was a Talystep 1 surface profiling instrument which was itself calibrated using a solid state artifacts of previously calibrated height; 90.75 nm. for the 100 nm. channel and 29.37 nm. for the 10 nm. channel. The behavior of the HECTOR transducer was measured six times immediately after the Talystep 1 was itself calibrated. A summary of the six measurements on each channel is shown in Table I.

The resolution (as evidenced by the standard deviation and peak-to-valley values) of the calibration at NIST was limited by response problems in the Talystep 1 as well as internal heating effects (when used in the Fixed Mode) inside the HECTOR transducer itself. The control system for the stylus height position on the Talystep 1 appears to have a resonance in the vicinity of 300 Hz. which is excited by the sharp rise and fall of the HECTOR target. This makes it difficult to read the leading and trailing edges of the artifact. In HECTOR the electronic circuit which controls the current during use of the Fixed Mode channels transmitted small amounts of heat into the transducer structure which in turn created small, but occasionally significant, dimensional changes which affected the output displacements. This parasitic heating influence has since been greatly reduced and the displacements are now repeatable to about one part in one thousand, as will be seen.

Table I. Calibration Measurements Made at NIST

Measurement Number	100. nm. channel	10. nm. channel
1	109.6	10.8
2	108.3	10.5
3	108.8	10.6
4	108.1	10.5
5	110.8	10.9
6	110.5	10.8
Mean	109.4	10.7
Std. Dev.	1.2	.14
Median	109.4	10.7
Peak-to-Valley	±1.4	±.2

Figure 3 shows three separate artifacts that have recently been generated by HECTOR in the 100. nm. channel and measured by capacitance gages in the AEH laboratory. Note that the mean amplitude of the artifacts has been normalized to 109.4 nanometers, the mean value established at NIST. However, the root-mean-square of the deviation of the individual measurements from the mean value is .082 nanometers, down by a factor of about 15 from the NIST measurements. Since the uncertainty introduced by noise in the metrology system is on the order of .03 to .05 nm. it would appear that the artifact itself is repeating within about one or two parts per thousand. This improvement in the Fixed Mode artifacts is due entirely to better management of the heat dissipation from the electronics associated with the fixed channels. These parasitic influences do not affect the User channel since the internal electronics are entirely bypassed in this mode of operation.

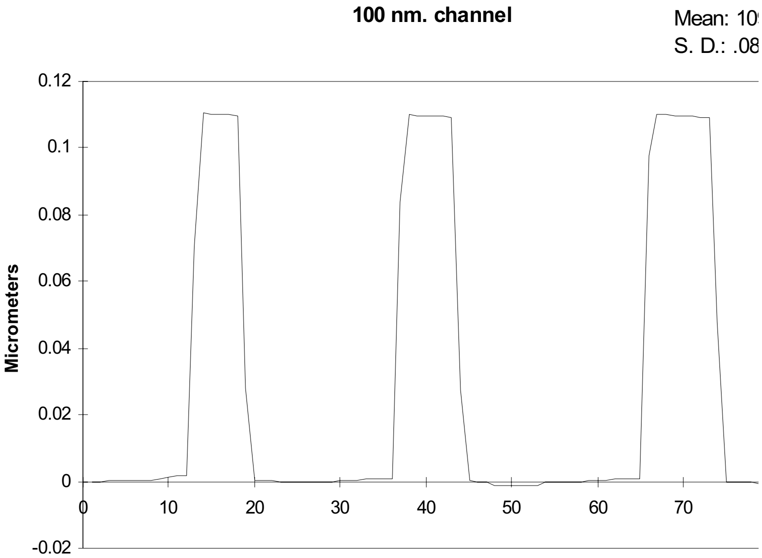

Figure 3. Typical artifacts generated in the 100. nm. channel

Measurement of the current in the coil of the Lorenz force transducer permitted calculation of the transduction effect based upon the calibration data for HECTOR's 100 nm. channel. The current in the coil was .39 amperes and mean measurement of displacement was 109.4 nm. so that the transduction effect is, transduction effect = 109.4/.39 = 280. nanometers per ampere.

The 100 nm. channel is selected for deriving the transduction effect from the NIST data because it had the least uncertainty in the reported displacements and the current, being larger, is assumed to offer more accurate readings on a standard ammeter. In this example the accuracy of the calibration is limited by both the Talystep 1 measurements at NIST (±1.4:109.4=±.0128) and the current measurement with an ammeter (±.005:.39=±.0128) resulting in an uncertainty of about 2.5% in the calculated transduction effect of 280. nm. per ampere.

The transduction effect in the User Mode may be determined much more accurately than in the Fixed Mode channels. Consider that the User Mode permits displacements up to about a micrometer and these may be measured much more accurately than the smaller Fixed Mode channels. The larger displacement permits the use of an interferometer measuring an integral number of wave lengths of light, a much more accurate process than measuring a fractional wave length. For example, an interferometer operating in the visible may have a resolution of about 5 nm. in optical path length difference. Measuring a displacement of 100 nm. (200 nm. of optical path length difference) could be done to an accuracy of about 2.5% whereas measuring a 1,000 nm. displacement (2,000 nm. optical path difference) would be done to an accuracy of about .25%, an order of magnitude improvement (note that other interferometric techniques may offer greater resolution). Also, the User Mode requires the instantaneous measurement of the applied current and the meter may have whatever precision is desired by the operator; four or more significant decimal places may be obtained. The User Mode is also immune to the influences of the parasitic heating of the Fixed Mode electronics. All of these considerations make the User Mode of operation much more accurate than any of the Fixed Mode channels and that applies to calibration as well as use.

In general, the accuracy of HECTOR's calibration, and its generated artifacts, is limited by the accuracy of the displacement measurements made in calibration rather than the accuracy of the current measurements.

3. CALIBRATION STABILITY

HECTOR's transduction effect is dependent upon a number of environmental variables. First, considering the User Mode calibration issues it is useful to recall equation (5) which states that the transduction effect, Xo/i, is equal to the product of the magnetic field, B, the length, l, of the coil in the field, the effectiveness ratio, E. R., of the transducer and the elastic stiffness, k, of the transducer. Any environmental variable that affects one of these quantities will have an influence on the transduction effect.

Of the common environmental factors only temperature and aging appear to have significant influences on the transduction effect. Atmospheric pressure, humidity and gravitational variation can be shown to have no influences on HECTOR's transduction effect. The thermal influences are limited to effects on the magnetic field, B, and the stiffness, k. Table II shows the magnitude of these thermal influences. The aging influences the effectiveness ratio, E. R., as well as the magnetic field, B.

Table II. Environmental Influences on HECTOR's Transduction Effect (User Mode)

Transduction Quantity	Influence on Transduction Effect, ppm	Notes
Thermal influences:		
Magnetic Field, B	+300. per K°	Niobium-Iron-Boron, -100 °C to +100 °C [1]
Stiffness, k	-180. per K°	6061-T6 aluminum, MIL-HDBK-5
Aging influences:		
Effectiveness ratio, E. R.	±.00053 per year	6061-T6 (Marschall & Maringer, 1977, p. 217)
Magnetic Field, B	-10. per year	estimated from related data

[1] From the supplier of the magnets.

The data in Table II are taken from the indicated sources. For the aging influence on the magnetic field the magnitude of the influence is inferred from the apparent stability of magnetic fields in other industrial application; reports of direct measurement of this aging effect have not been found but the value shown should prove to be conservative.

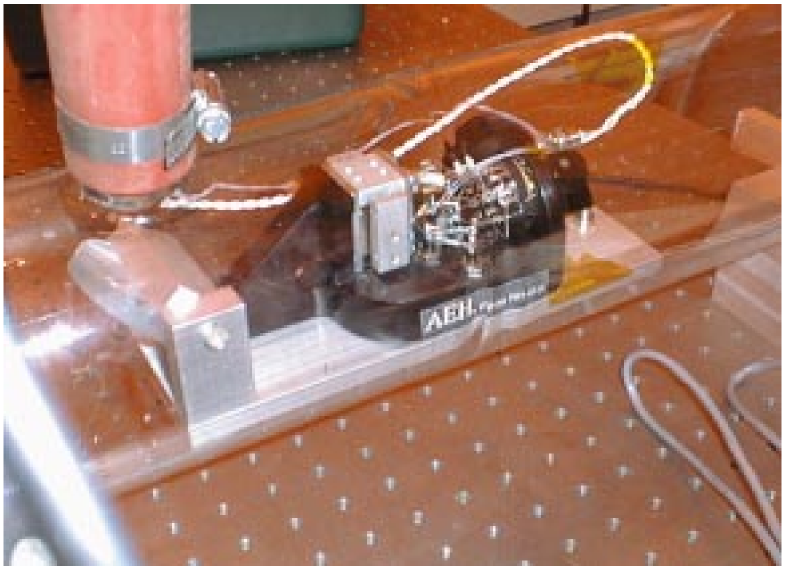
Figure 4. HECTOR installed in the vacuum bottle to test an interferometer.

Review of the data in Table II suggests that artifacts generated in the User Mode should be repeatable to one part in one thousand (1:1,000) in normal industrial environments (±10 C°). Furthermore, in carefully controlled laboratory conditions (±1 C°) HECTOR's User Mode should be repeatable to one part in ten thousand (1:10,000) or even better. The aging influences suggest that re-calibration of HECTOR should not be necessary in less than ten years under normal full-time use and a required repeatability of one part in ten thousand (1:10,000) over that time period. However, the data for the aging effects on the magnetic field are not complete so users of HECTOR who require very high accuracy may wish to check the calibration of the transducer more frequently.

4. TYPICAL CALIBRATION ARTIFACTS GENERATED BY HECTOR

HECTOR has been used to validate an interferometric metrology facility (Hatheway, 1998). Figure 4 shows HECTOR inside the glass vacuum bottle of the facility. HECTOR's target is obscured by a mirror that folds the horizontal measurement leg of the interferometer and directs it in a vertical line to the target. The 109.4 nm. Fixed Mode artifact (from the 100. nm. channel) was used to assure the operators of the facility that they had eliminated all spurious influences on the interferometer's operation. Typical artifacts from this channel are shown in Figure 3, above.

However, of more interest to process control are the artifacts that may be generated in the User Mode of operation. Figure 5 shows a series of artifacts generated in the User Mode with a current of .038 amperes. Three artifacts were generated with a

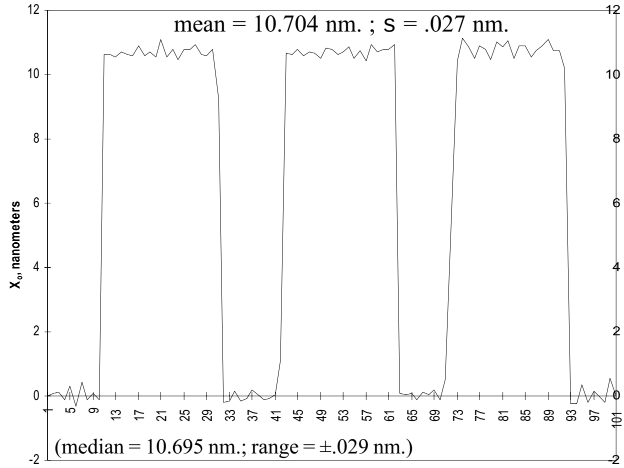

Figure 5. HECTOR's performance at i=.038 amperes (User Mode).

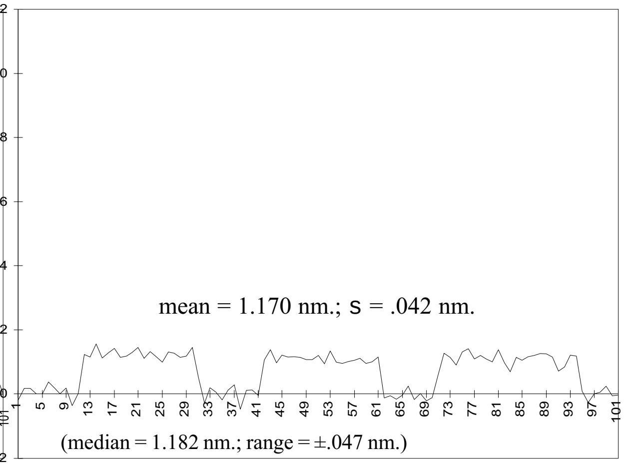

Figure 6. HECTOR's performance at i=.0042 amperes (User Mode).

mean height of 10.704 nm. and the difference between the largest and smallest was .058 nm. (±.029 nm. deviation from the median).

Similarly, Figure 6 shows a series of artifacts generated in the User Mode with a current of .0042 amperes. These artifacts are about an order of magnitude smaller than those shown in Figure 5 as would be expected since the current is about an order of magnitude smaller. The mean value of the artifacts in Figure 6 is 1.170 nm. and all the values are within ±.047 nm. of their median.

The smoothness of the data plotted in Figure 3 is due to a long averaging time, 2 seconds, for the capacitance bridge which measured the capacitance of the gages. In Figures 5 and 6 the averaging time was .5 seconds but the recording time was the same, about 5 seconds. In spite of the visual impression to the contrary, the User Mode data shown are more repeatable than the Fixed Mode data. This is as one would expect since the Fixed Mode data are influenced by some parasitic heating from the electronics in the transducer.

Evaluations of the capacitance gage metrological setup have shown that the noise it contributes to the measurement are about .030 to .050 nm. (on a root-mean-square basis). It appears that the variation in the artifacts shown in Figures 5 and 6 (generated in the User Mode) is dominated by the noise in the metrology instruments With this in mind it seems that HECTOR's artifacts generated in the User Mode are repeating within a zone that is between one part in a thousand and one part in ten thousand (1:1,000 and 1:10,000), about what one would expect.

5. CONCLUSIONS

A new compound transducer has been developed by coupling a classic Lorenz force transducer to a new (patented) elastic transducer. The compound transducer converts an electrical current into a mechanical displacement. The combined effect is shown to be linear, hysteresis free and very stable in both the time and temperature domains. One form of the transducer has been developed to provide small calibration artifacts in the metrology region from about 100 nm. to below an angstrom, the trans-nanometer region, where the wave length of light is too coarse for direct use in metrology.

The new transducer is called HECTOR and it is capable of generating physical artifacts throughout this trans-nanometer region by creating very accurate position steps in a form readable by metrology instruments; profilometers, interferometers and atomic force microscopes. HECTOR may be calibrated in a number of ways, many of them traceable to the wave length of light. HECTOR's design lends itself to direct calibration in an interferometer.

HECTOR's artifacts are accurate, stable and highly repeatable. They should greatly improve the metrology of small features in surface physics, process control and research.

HECTOR-generated artifacts have three valuable attributes:

1) there is no downward limit on their size,
2) their accuracy and repeatability (as a fraction of the artifact size) is independent of the size of the artifact and
3) the accuracy of the artifacts depends upon the accuracy of calibration, i. e. our ability to subdivide the wave length of light.

With the present calibration technology (interferometers) HECTOR offers two orders of magnitude or more reduction in the uncertainty compared to existing artifacts in the trans-nanometer region.

6. REFERENCES

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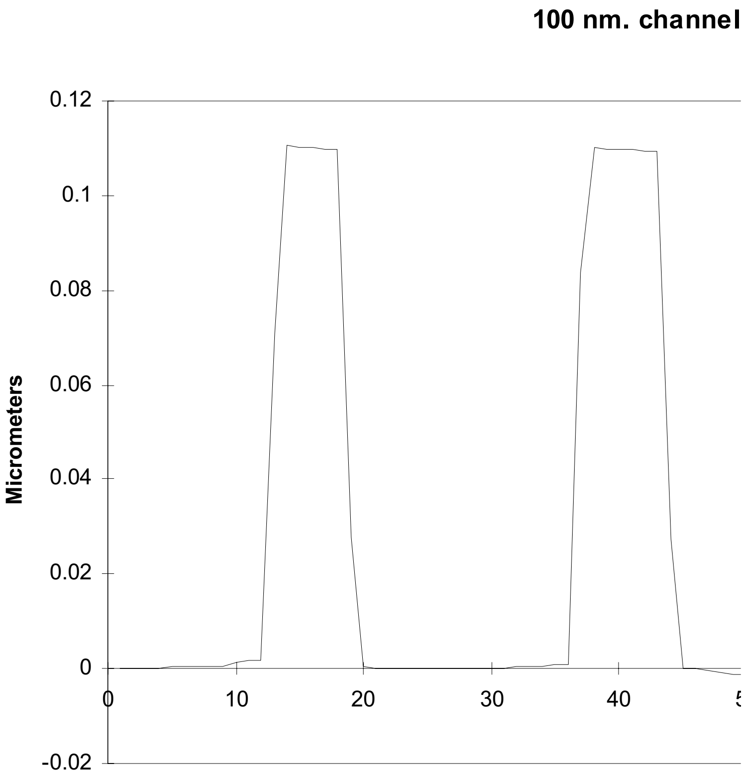
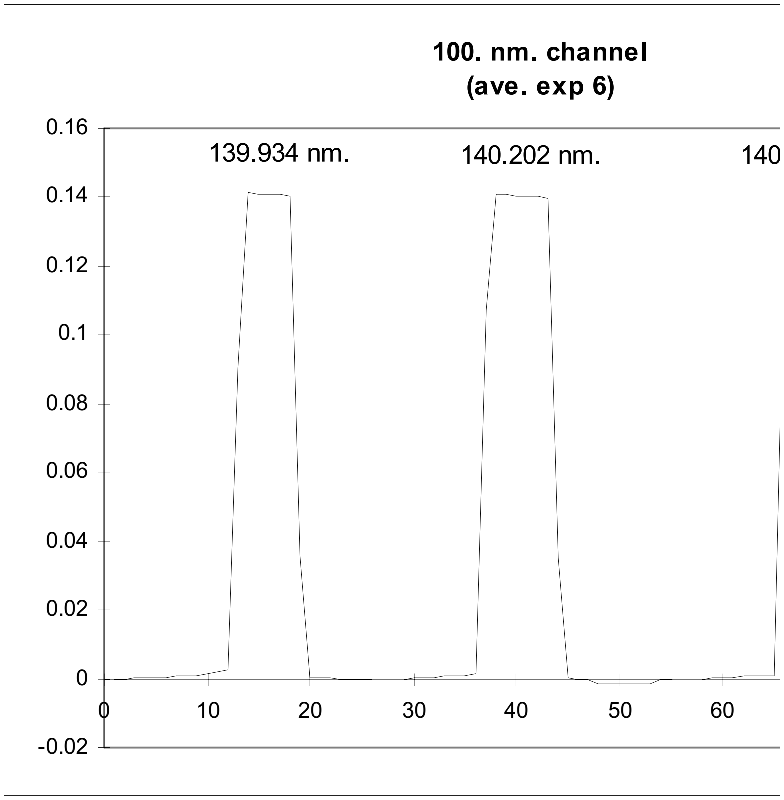
Note: “Ångstrom” and “HECTOR” are trade marks of Alson E. Hatheway Inc.


100 nm. channel
Micrometers
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
10
20
30
40



During the behavioral study the 100. nm. and 10. nm. artifacts generated by the corresponding fixed-size channels were measured using the company's instrumentation. This is comprised of custom-made low noise capacitance gages, an Andeen-Hagerling 2500E capacitance bridge and a commercial multimeter. Only the capacitance bridge had been recently calibrated so all the set-up was not completely calibrated. However, it was very stable and repeatable so relative measurements could be made for engineering purposes. The study showed the following results:

Artifact	Measurement	Repeatability
100. nm.	103. nm.	±1%
10. nm.	10.5 nm.	±1%

The engineering laboratory set-up had a background noise level equivalent to about .5 nanometers instantaneously and drivt of about 5 nanometers per minute so it would appear that most of the repeatability error was in the capacitance gage metrology system.