Nanometer-level Feedback-Stabilized Interferometric Aligning and Gapping X-ray Exposure System

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Sponsorship

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An experimental high-precision, X-ray exposure system has been constructed that employs Interferometric Broad-Band Imaging (IBBI) for alignment. The IBBI scheme utilizes grating and checkerboard type alignment marks on mask and substrate, respectively, which are viewed through the mask from outside the X-ray beam at a Littrow angle of 16 degrees with f/10 optics and a 110 mm working distance. Each mark consists of two gratings (or checkerboards) of slightly different periods, p_1 and p_2, arranged so that p_1 is superimposed over p_2, and p_2 over p_1 during alignment. Alignment is measured from two identical sets of moiré fringes, imaged onto a CCD, that move in opposite directions as the mask is moved relative to the substrate. Alignment is determined from the relative spatial phase of the two fringe sets, measured with a high-sensitivity frequency-domain algorithm.

The gap can be determined and controlled with a previously described Transverse Chirp Gapping (TCG) scheme, which permits interferometric sensitivity to gap using a single mark on the mask. The gap information is encoded into the spatial phase of a pair of fringes, which are observed with the same microscope as the IBBI fringes.

As described above, the IBBI alignment signal is encoded in the spatial phase of interferometric fringes. These fringes can be displaced by half a fringe period in either direction without ambiguity. To break the phase ambiguity accompanying larger displacements, another indicator of alignment must be included. In the past this indicator has consisted of a second set of fringes of larger period than the first, as well as a set of three diffracting bars, two on the mask and a central bar on the wafer. Since both sets of IBBI fringes move quickly and at similar rates, it is difficult for an observer to estimate the misalignment by eye, or to tell how far, or even in which direction, the fringes are misaligned. An algorithm must be relied upon to extract the misalignment from the coarse and fine IBBI fringes. The coarsest alignment was done with simple peak detection of the three diffracting bars, which was found to be highly sensitive to noise.

An alternative means of eliminating phase ambiguity was devised with the intent of: 1) expanding the acquisition range, 2) making the degree of misalignment apparent to a human operator, 3) employing the same IBBI spatial-phase algorithm for the analysis of coarse and fine marks.

To accomplish these goals we use the same fine grating pairs with superimposed p1 and p2 gratings, but add a periodic array of diffracting bars on mask and wafer with the same spatial period as the IBBI fringes, as depicted on the right side of the IBBI fringes I Figure 11. Each bar consists of a linear grating with a 1 micron period to back-diffract 1st order beams to the IBBI microscope. The acquisition range of a given bar array is equal to its period. In the case of the bar array on the right, the acquisition range is about 30 microns. Another mark, such as a second bar array with a larger period (shown on the left of the fringes in Figure 11), can be used to extend this range if necessary.

Using a periodic bar array with the IBBI spatial phase algorithm not only yields improvements in coarse alignment detection and reduced sensitivity to noise,

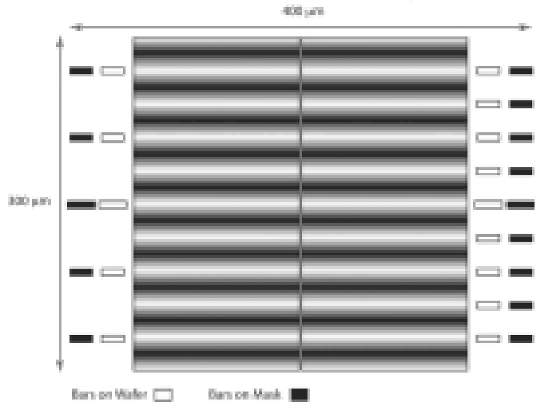

Fig. 11: Improved IBBI alignment mark. Coarse alignment matches the spatial phase of the bars on mask and wafer. Fine alignment matches the spatial phase of the interference fringes (simulated in this schematic). Spatial phase matching between bars and fringes avoids 1-fringe-cycle misalignment.

but also permits a comparison between the spatial phase of the bars and fringes. With the new marks, alignment proceeds by analyzing first the spatial phase of the two bar arrays with the same period as the fringes (on the right in Figure 11), then the spatial phase between one set of bars and one set of fringes, and finally the spatial phase between the two sets of fringes. The fringe-bar phase was found to be the most sensitive test of a common error: a misalignment of exactly one fringe cycle. In the aligned condition all three phase parameters (bar-bar, fringe-bar and fringe-fringe) have zero spatial phase Figure 12(a), but a misalignment by one fringe cycle is unambiguously indicated by a 180 degree phase difference between fringes and bars Figure 12(b). In other words, we can now detect this common error by an obvious misalignment of bars and fringes. If undetected, this condition would result in an exposure misalignment of >500 nm. To put this in perspective, the maximum alignment error we can tolerate in many applications is <5 nm.

Using the new alignment marks, the automatic alignment algorithm was extended to include rotation, as well as X and Y alignment. Three microscopes are used, with two microscopes observing X and Y marks in the center of the mask, and a second microscope dedicated to a Y mark near the edge of the mask. Once the mask and wafer are manually pre-aligned to within the acquisition range of the bar marks, the algorithm quickly iterates to find the full planar alignment condition. Typically, the alignment is performed in 4 iterations of about 1 second per iteration. Figure 13 shows data for the three marks when running open-loop (first row) or closed loop (second row). The mean and standard deviation in rotation is larger than statistics for X and Y marks at the center of the mask due to the finite step size of the DC servo drive (0.5 arcsec) used for rotational corrections. A piezo stage controls X and Y motion with sub-nanometer precision.


(a) (b)

Fig. 12: (a) Aligned position: Spatial phase matched between bar-bar, fringe-bar, and fringe-fringe. (b) Misaligned position: fringes aligned, bars apparently aligned, but fringe-bar phase shift of 180 deg. indicates 1-fringe-cycle misalignment.

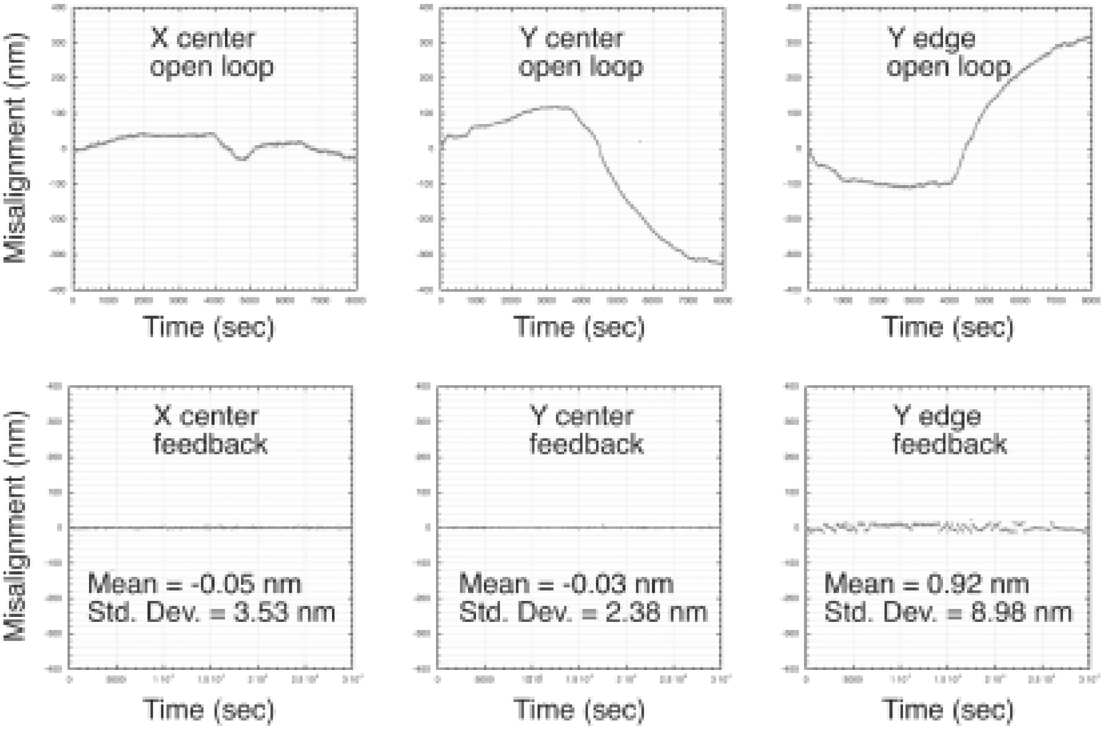

Fig. 13: Data from three IBBI images with and without feedback. X-center and Y-center were taken from adjacent marks at the center of the mask pattern. Y-edge was taken from a mark 1 cm away from the center.

The unique collection of capabilities of IBBI alignment, TCG gapping, and X-ray axis alignment are being employed in the fabrication of a variety of electronic and optical devices. For example, work is being done on the IBBI system to fabricate a double-gate n-MOS transistor using direct alignment of the gates. Aligned exposures (with the upper gate feature in resist) suggest this will be feasible. Figure 12 shows such a double-gate structure, with upper gate mimicked by resist, and the lower gate is seen as the light trapezoidal region. Measurements taken from the center of the upper gate feature to the edges of the lower gate suggest alignment to <5 nm.

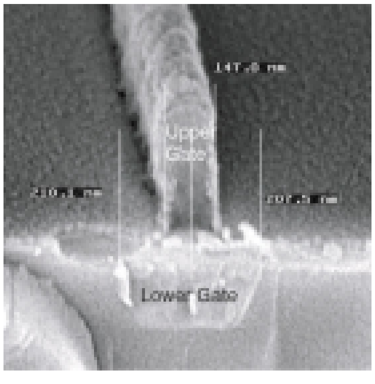

Fig. 14: SEM micrograph of upper gate structure in resist aligned to a lower gate buried in LTO. Alignment was done using X, Y, and rotation feedback throughout the X-ray exposure. SEM measurements suggest alignment to <5 nm