MULTI-LAYER, SELF-ALIGNED VERTICAL COMBDRIVE ELECTROSTATIC ACTUATORS AND FABRICATION METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based on Provisional application 60/192,097 filed Mar. 24, 2000, which is herein incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to micro-electromechanical systems (MEMS). More particularly, it relates to vertical comb-drive electrostatic actuators and fabrication methods.

BACKGROUND ART

Microstructures fabricated using silicon integrated processing techniques are used in a wide variety of sensing, actuating, and optical applications. One particularly useful device is a comb-drive actuator, which consists of two comb-like structures, one mobile and one stationary, whose fingers are interdigitated. When a potential difference is applied to the alternating fingers, a resulting electrostatic force causes the mobile fingers to move to maximize the overlap area. While the force provided by each finger is quite small, including a large number of fingers in the comb drive allows for application of relatively large forces using low voltages, particularly when there is a large capacitive overlap area between two adjacent fingers. Comb drives also provide a method for accurate position measurement by sensing of the capacitance of the fingers.

Comb drives are differentiated by the plane of motion of the stationary and mobile combs with respect to one another. Linear or lateral comb-drive actuators provide translational motion in a single plane as the two comb devices move from being relatively spaced apart to being fully interdigitated. The two comb structures remain in the same plane during actuation, with the stationary comb being fixed to a substrate, and the mobile comb moving with respect to the substrate. Examples of lateral comb drives are disclosed in U.S. Pat. Nos. 5,025,346, issued to Tang et al., and 5,998, 906, issued to Jerman et al.

It is often desirable to create out-of-plane actuation of various microstructures, such as rotation of mirrors about an axis parallel to a substrate. These rotating mirrors can be used individually or in array form for applications such as adaptive optics, visual displays, or fiber-optic switching. Vertical comb-drive actuators provide rotational motion or translational motion perpendicular to a substrate. A micromachined electrostatic vertical actuator is disclosed in U.S. Pat. No. 5,969,848, issued to Lee et al. The device of Lee et al. contains a set of vertical comb drives, with each drive capable of deflecting one edge of a square mirror. By relying on an asymmetric distribution of electrical fields when a bias voltage is applied between stationary and movable comb fingers, the device of Lee et al. allows a small vertical (i.e. out of the plane of the comb fingers) motion of each mirror edge, at most 1.5 μm.

Larger movements and more simplified fabrication techniques are provided by staggered vertical comb drives, in which the stationary and moving comb drives are positioned parallel to one another, but with the plane of the moving comb above the plane of the stationary comb. The stationary comb fingers are an integral part of the substrate, while the moving comb is fixed to the substrate only through flexures. Applying a voltage between the two comb layers causes the moving comb teeth to be attracted to the stationary teeth and move to increase the overlap area, thereby exerting a force on the moving comb. Conventional fabrication techniques for vertical comb drives using standard photolithography processes require multiple steps for patterning the comb fingers. First, one set of comb teeth is fabricated on a first wafer layer. A second wafer layer is then bonded on top of the first wafer layer, followed by patterning and etching of a second layer to form the second set of comb teeth. The two wafer layers must be aligned to a very high precision; typical applications require comb fingers of 2 μm wide with a 6 μm separation distance, so that adjacent overlapped fingers are separated by only 2 μm. Fabrication of vertical comb drives using this technique is prone to alignment problems. The steppers used to align the individual die on a wafer typically have a lateral resolution of ±0.25 μm. This resolution places a lower limit on the gap between adjacent comb fingers of about 2 μm. Because two adjacent fingers are at different potentials during operation, they cannot contact each other. At high actuation voltages, errors in alignment of the fingers can cause sideways motion and instability in the comb drive. As a result, conventional fabrication techniques typically have low production yields.

There is a need, therefore, for a vertical comb drive that can be fabricated in fewer steps than required by conventional fabrication methods, and that provides accurate alignment between two layers of comb fingers without requiring complicated alignment procedures.

SUMMARY

The present invention provides a multi-layer vertical comb drive actuator in which first and second comb fingers are simultaneously fabricated from a single multi-layer substrate. Because the fingers are fabricated together, the tedious alignment of the first and second fingers, required for fabricating conventional vertical comb-drive actuators, is avoided. Alignment is a direct result of the mask used in fabrication; thus the device is referred to as self-aligned. Each finger has two vertical conductive layers separated by an insulating layer or an air gap, and movement is provided by attraction of opposite layers of the first and second comb fingers.

The present invention provides a multi-layer vertical comb drive actuator containing a first comb structure having a plurality of first comb fingers, and a second comb structure having a plurality of second comb fingers. The second comb fingers extend from a comb bridge connected to the substrate through one or more flexures allowing vertical movement or rotational movement about an axis, and are positioned to be interdigitated with the first comb fingers. A movable element is attached to the rotatable flexure and coupled to the second comb structure. In one embodiment, both the first comb fingers and the second comb fingers may include first and second conductive layers electrically isolated from each other by an insulating layer or air gap. The first conductive layers of the first comb fingers may be substantially aligned with the first conductive layers of the second comb fingers, and the second conductive layers of the first comb fingers may be substantially aligned with the second conductive layers of the second comb fingers. In an alternate embodiment, the second comb fingers may have only a first conductive layer in vertical alignment with the first conductive layer of the first comb fingers. In a further alternative embodiment, the second comb fingers have first and second